NASA Conference Publication 2460

Upper and Middle Atmospheric Density Modeling Requirements for Spacecraft Design and Operations

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Proceedings of a workshop held in
Huntsville, Alabama
November 19-21, 1985

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Upper and Middle Atmospheric Density Modeling Requirements for Spacecraft Design and Operations

Edited by
M. H. Davis and R. E. Smith
Universities Space Research Association
Boulder, Colorado

D. L. Johnson
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

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PREFACE

A series of meetings with engineering organizations involved both in designing and developing new satellite systems and sub-systems and in planning missions for and operating current space vehicles led to the realization that there was a communications gap between these engineering/operational organizations, the "users" of natural ambient environmental data, and the scientific and support organizations that were responsible for obtaining, collating, and supplying these environmental data to them. The users were unaware of the limitations of and restrictions on the use of the data and models while the suppliers were unaware not only of how the data were being used but also of the data that the users were obtaining through analyses of responses of operational systems that could be attributed to variations in the natural ambient parameters.

The neutral ambient atmospheric density above 50 kilometers is one natural environment parameter where not only was the communications gap significant but also where lack of knowledge and the variability of the parameter itself were causing both design and operational penalties.

It was decided that a workshop similar to the Workshop on Satellite Drag held on March 18-19, 1982, at NOAA's Space Environment Laboratory in Boulder, Colorado, could provide a forum for discussing these problems and thereby for developing a rationale and plan for possible solutions. There were 55 attendees, representing 32 organizations. Both sides were well represented; problems and ideas were exchanged, discussed, and recommendations for solutions were formulated.

In the body of this report, we present synopses of the presentations and discussions from the editors' notes along with selected presentation material. Also included are summaries prepared by session chairpersons.

Finally, as a result of his attending this meeting, Dr. Kenneth Moe has provided comments on differences between atmospheric models and measurements.

R. E. Smith
M. H. Davis

INTRODUCTION

The purpose of this workshop was to allow an interchange of ideas and to establish a communications link between the users of models of the neutral atmosphere and the developers of these models. On the first day the concentration was on operations and modeling at orbital altitudes including a discussion of the solar activity parameters that have been associated with variations in the neutral atmosphere at orbital altitudes. On the second day the concentration was on the middle atmosphere, 50-90 km, the entry region for operational vehicles. It is essential that the models produce consistent and accurate values of the atmospheric thermodynamic parameters from the ground up through the thermosphere for all latitudes, longitudes, times, seasons, and phases of the solar cycle. There is only one model available at this time which meets all of these requirements--the Global Reference Atmosphere Model (GRAM), which joins an updated version of the 1970 Jacchia model of the thermosphere with an expanded version of the Groves model of the middle atmosphere which is then joined to a 4-D model of the atmosphere from the surface to 25 kilometers.

Satellite lifetime prediction is a typical application of models of the thermospheric density. Density data are required in the satellite tracking programs used by NORAD and by the Navy for precision orbits. Density is also important in satellite attitude control (desaturation of attitude control systems--jitter in precision pointing) and in precision orbit positioning. Atmospheric composition must also be considered: it influences the drag coefficient, and neutral atomic oxygen, a principal constituent, causes deterioration of exposed surfaces. For drag, the neutral density is of primary importance. Plasma drag has been observed for particular satellites in a research context, but its effects are swamped by uncertainties in neutral drag.

Day-two discussions on the middle atmosphere, in the context of this meeting that portion of the atmosphere between ~50 km and ~90 km, included presentations by both users and modelers. System and mission planners make use of the statistics on small scale atmospheric variations established by repeated runs of the GRAM to study Space Shuttle entry scenarios and the proposed use of the middle (~80 km) atmosphere for braking of the Aero-assisted Orbital Transfer Vehicle (AOTV).

The remainder of the workshop was devoted to formulating recommendations for resolving problems revealed during the workshop.

In addition to the speakers listed on the agenda, other attendees participated in the program as discussants. Their prepared materials are included at appropriate locations in these proceedings.

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WORKSHOP SUMMARIES AND CONCLUSIONS

R.E. Smith, M.H. Davis

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SUMMARY OVERVIEW

Issues	Recommendations
Small-scale structures are not modeled.	Develop statistics or bounds for small scale structures for inclusion in models
Dynamics are not included	Investigate feasibility of including in models
Global reference atmosphere model needs revision and updating	Use current (post 1974) data to update model
Atmospheric parameter and ancillary data measurement programs are being stopped	Continue data acquisition programs to establish a required long-term data base
Lack of communication between users and modelers	Establish a clearinghouse to insure a timely exchange of recent developments

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SUMMARY - ISSUES AND RECOMMENDATIONS

ISSUE 1: PREDICTION OF SOLAR AND GEOMAGNETIC ACTIVITY: The ability to predict atmospheric density depends strongly on the ability to predict solar EUV (models currently use its approximate correlate, F10.7) and geomagnetic indices (Kp).

For design purposes, bounds are needed for solar and geomagnetic indices for time periods several years in the future. For satellite operations (viz. NORAD satellite orbit determination and Navy satellite precision orbit adjustment), the ability to predict up to several days into the future would be valuable.

RECOMMENDATION: a) The uncertainty in predictability of these quantities should be quantified as a function of prediction interval and solar cycle phase.
b) Research should be supported to improve the reliability of solar variability predictions.

ISSUE 2 - SMALL SCALE STRUCTURES IN MODELS: The models now being used are able to reproduce observed atmospheric density with a standard deviation of about 15% after the actual Kp and F10.7 indices are known (hindcasting). It is believed that a significant part of the remaining discrepancy arises from failure to represent small scale structures (of the order of 5 degrees in latitude or longitude).

RECOMMENDATION: Although individual gravity waves cannot be modeled, it may be possible to upgrade present models to include statistics or bounds for small scale structures using gravity wave theory. Development of a gravity wave climatology should be supported.

ISSUE 3 - INCLUSION OF WIND-FIELDS: Present models fail to treat dynamical processes (winds). This defect is of importance especially at high latitudes.

RECOMMENDATION: An attempt should be made to integrate wind-field information into the models used by the engineering community. The thermospheric GCM's being developed are important in this context.

ISSUE 4 - IMPROVED COMMUNICATION BETWEEN USERS AND MODELERS:
Model users generate information that can be valuable feedback to the modeling process, provided effective communication exists between the users and the modelers, and the models allow for incorporation of new information. On the other

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side, the modelers are continually working to upgrade their models and add new features.

RECOMMENDATION: Models should be capable of accommodating information from users as it becomes available, and an effective clearinghouse for feedback should be established and maintained. Information on new model developments and features should be provided in a timely fashion.

ISSUE 5 - IMPORTANCE OF CONTINUITY OF "ROUTINE" MEASUREMENTS: The measurements required to know the state of the thermosphere are not now being routinely made. Rocket programs are disappearing. Routine measurements of quantities such as F10.7 and geomagnetic quantities are dropping by the wayside. There is no current program to derive density or other atmospheric quantities from satellite tracking and there are no current satellites specifically for this purpose.

For understanding of the atmosphere and its variability, it is vital to have a continuous long-term data base.

RECOMMENDATION: If possible, routine measurements of thermospheric parameters, and of solar and geomagnetic quantities should be continued and encouraged in order to continue the long-term data base that already exists.

The feasibility of using routine satellite orbit tracking information to derive upper atmosphere information should be studied.

The scientific community should plan and support a "thermosphere weather" satellite or payload for the shuttle and space station to monitor thermospheric conditions. It is also of vital importance to monitor routinely geomagnetic quantities, solar ultra-violet, solar and cosmic particles, and the solar wind.

ISSUE 6 - STANDARDIZATION: While there is some advantage to parallel efforts in modeling the thermosphere, there appears to be unnecessary duplication of effort both by modelers and users.

RECOMMENDATION: There should be a careful evaluation of whether it may be desirable to standardize the atmospheric model and the management of modeling and associated research. The user community needs models that are reliable and computationally efficient; Government officials require standard models that can be called out in specifications; those doing research and development on models need frameworks that will allow for inclusion of new data and new factors. These needs, which are somewhat in conflict, must be carefully weighed.

ISSUE 7 - NEW DATA SOURCES FOR THE MIDDLE-ATMOSPHERE: New data sources for density and dynamics of the middle atmosphere have appeared during the past ten years, including: satellite radiometry, limb scanners, Rayleigh scatter lidar, MST radar, shuttle drag measurements during re-entry, occultation of astronomical sources.

RECOMMENDATION: The capabilities of these new techniques should be carefully assessed, and this new information should be added to the data base of user models.

ISSUE 8 - THERMOSPHERIC GCM: Theoreticians R. Roble and T. Killeen are making rapid progress in development of theoretical models of thermospheric dynamics.

RECOMMENDATION: The modelers should study and be guided by the TGCM developments.

ISSUE 9 - PREFERENCE FOR THE OLD JACCHIA MODELS: While the "old" Jacchia models J64, J70 and its updates, appear to be as good as newer models for satellite drag analysis, they do not give correct results for composition, which is needed for studies of glow and atomic oxygen erosion, and can affect the drag coefficient. Another issue is that by continuing to use the old models, the user community is not taking notice of recent trends in research such as the use of spherical harmonics.

RECOMMENDATION: These points are part of the standardization issue and need to be considered in that context.

ISSUE 10 - LACK OF SUPPORT FOR RESEARCH ON THE NEUTRAL ATMOSPHERE: Research into the neutral middle and upper atmosphere, particularly the region from about 60 to 120 km, is not favored for support by NASA Headquarters or other Government agencies.

RECOMMENDATION: The Workshop recommends that a way be found to stimulate funding for research directed toward studying properties, dynamics, and measurement techniques of the neutral middle and upper atmosphere.

ISSUE 11 - SPECIFIC COMMENTS AND RECOMMENDATIONS ON THE GRAM MODEL: There was general agreement on the desirability of a unified model of the atmosphere from the ground up. The GRAM is such a model and has been remarkably successful. An important requirement is that the model encompass the "ignorosphere" from 60 to 100 km for which there is little data.

The Workshop endorsed the work of Justus and the Georgia Tech Group in developing and maintaining the GRAM model.

Specific recommendations relating to the GRAM itself:

1) use monthly rather than seasonal reference atmospheres.

2) develop a better specification of the mean.

3) devise a better means for describing fluctuations and their spectral distribution and correlation. (Care should be used in applying the GRAM model for study of small scale structures; spurious results can arise from using a vertical step size that is too small.)

4) adjust zonal means to correct for planetary waves one and two.

ORBITAL ATMOSPHERE MODEL USERS

Chairperson: G. Nurre

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SATELLITE LIFETIME PREDICTION

Gerald Wittenstein, NASA/Marshall Space Flight Center

Satellite lifetime predictions are critically dependent on the ability to forecast future solar and geomagnetic activity. These quantities are inputs to the atmospheric model with which values of atmospheric density are computed along a projected orbital path. Density values are combined with the predicted ballistic coefficient timeline to compute drag and predict decay histories. The major uncertainty in making predictions that pertain to time periods that are years in the future is in the solar and geomagnetic activity projections, although the ballistic coefficient is also frequently in doubt.

Reliable lifetime predictions are of great importance. Lifetime in terms of years of on-station operation and reboost requirements are major drivers of system costs. For the space station a major issue is to predict when reboost is necessary. For low solar activity (sunspot number 50) it is estimated that 1000 lb of propellant are required for reboost each year, while for high activity (sunspot number 200) 10,000 lb are required.

Comparisons between actual and predicted orbit lifetimes show large differences that are due mostly to the uncertainties in predicting solar/geomagnetic activity. When the actual solar/geomagnetic indices that were observed during the orbital lifetime are put into the models during post-flight orbital analyses, the models work quite well, within about 10 - 15 percent in lifetime. High inclination orbits may be expected to exhibit the greatest variability (Roble).

Given present knowledge, solar cycle uncertainties are unavoidable. A reasonable procedure is to go with the best forecasts available, and try to allow for variations by estimating lifetimes for both nominal and plus two-sigma solar activity levels. Short term variations are essentially unpredictable.

USER SUMMARY Satellite lifetime

In summary, while present density models are adequate for planning, the inputs to them, particularly solar/geomagnetic activity indices, are unreliable.

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ORGANIZATION: EL25

CHART NO.:

MARSHALL SPACE FLIGHT CENTER

SATELLITE LIFETIME

NAME: G. WITTENSTEIN

DATE: NOVEMBER 18, 1985

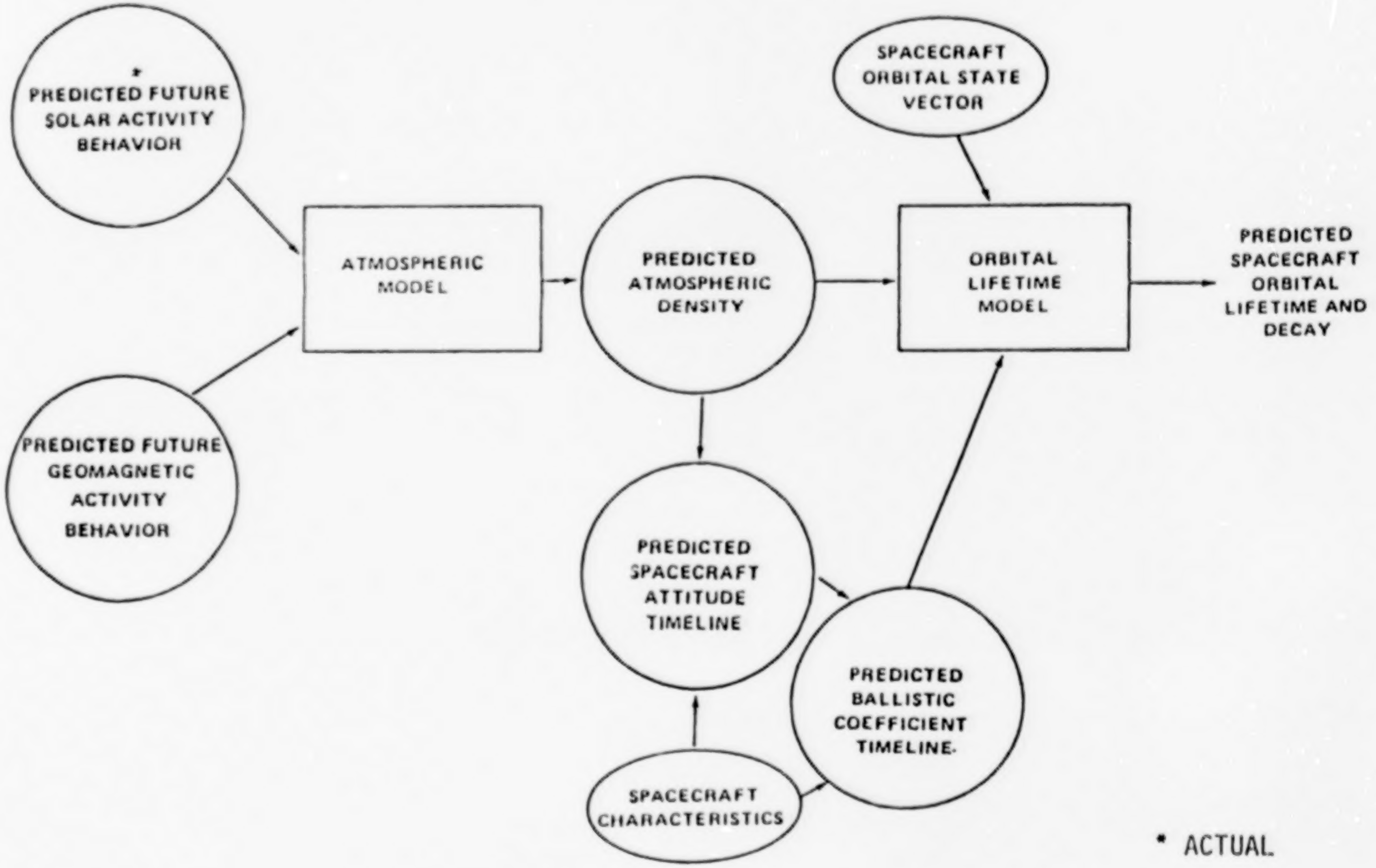
oo INTRODUCTION
oo DESIGN PROBLEMS CONCERNING SATELLITE LIFETIME

oo THE UNAVOIDABLE - EFFECT OF SOLAR CYCLE UNCERTAINTIES

oo MISSION PLANNING EFFECTS

OO SUMMARY

SOLAR PREDICTIONS AND SPACECRAFT ORBITAL LIFETIME


* PREDICTED FUTURE SOLAR ACTIVITY BEHAVIOR
PREDICTED FUTURE GEOMAGNETIC ACTIVITY BEHAVIOR
ATMOSPHERIC MODEL
PREDICTED ATMOSPHERIC DENSITY
SPACECRAFT ORBITAL STATE VECTOR
ORBITAL LIFETIME MODEL
PREDICTED SPACECRAFT ORBITAL LIFETIME AND DECAY
PREDICTED SPACECRAFT ATTITUDE TIMELINE
PREDICTED BALLISTIC COEFFICIENT TIMELINE.
SPACECRAFT CHARACTERISTICS

* ACTUAL

NASA/MSFC/ES-81

ORGANIZATION: EL25	**MARSHALL SPACE FLIGHT CENTER**	NAME: G. WITTENSTEIN
CHART NO.:	SATELLITE LIFETIME	DATE: NOVEMBER 18, 1985

00 DESIGN PROBLEMS CONCERNING SATELLITE LIFETIME

- 0 SYSTEM COST - $ vs YEARS OF OPERATION, REBOOST
- 0 SATELLITE CONTROL SYSTEM DESIGN, SPACE TELESCOPE, SKYLAB, SPACE STATION
- 0 ORBIT ALT MAINTENANCE - REBOOST/ORBIT TRIM SYSTEM - SPACE STATION
- 0 SATELLITE MATERIAL DETERIORATION - O (ATOMIC OXYGEN) - ALL

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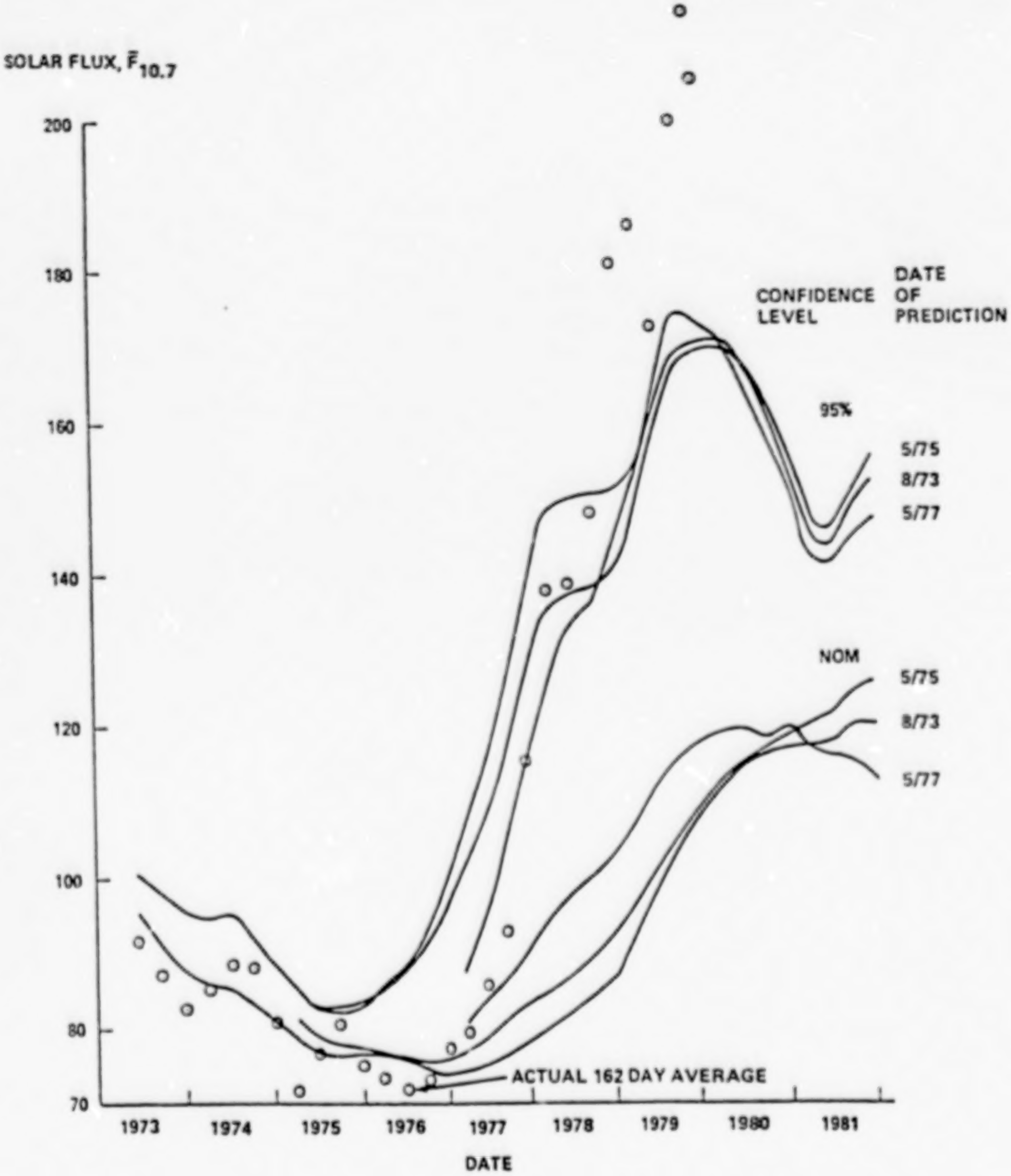
CHART NO.:	SATELLITE LIFETIME	DATE: NOVEMBER 18, 1985

00 THE UNAVOIDABLE - EFFECT OF UNCERTAINTIES
IN PREDICTING SOLAR ACTIVITY

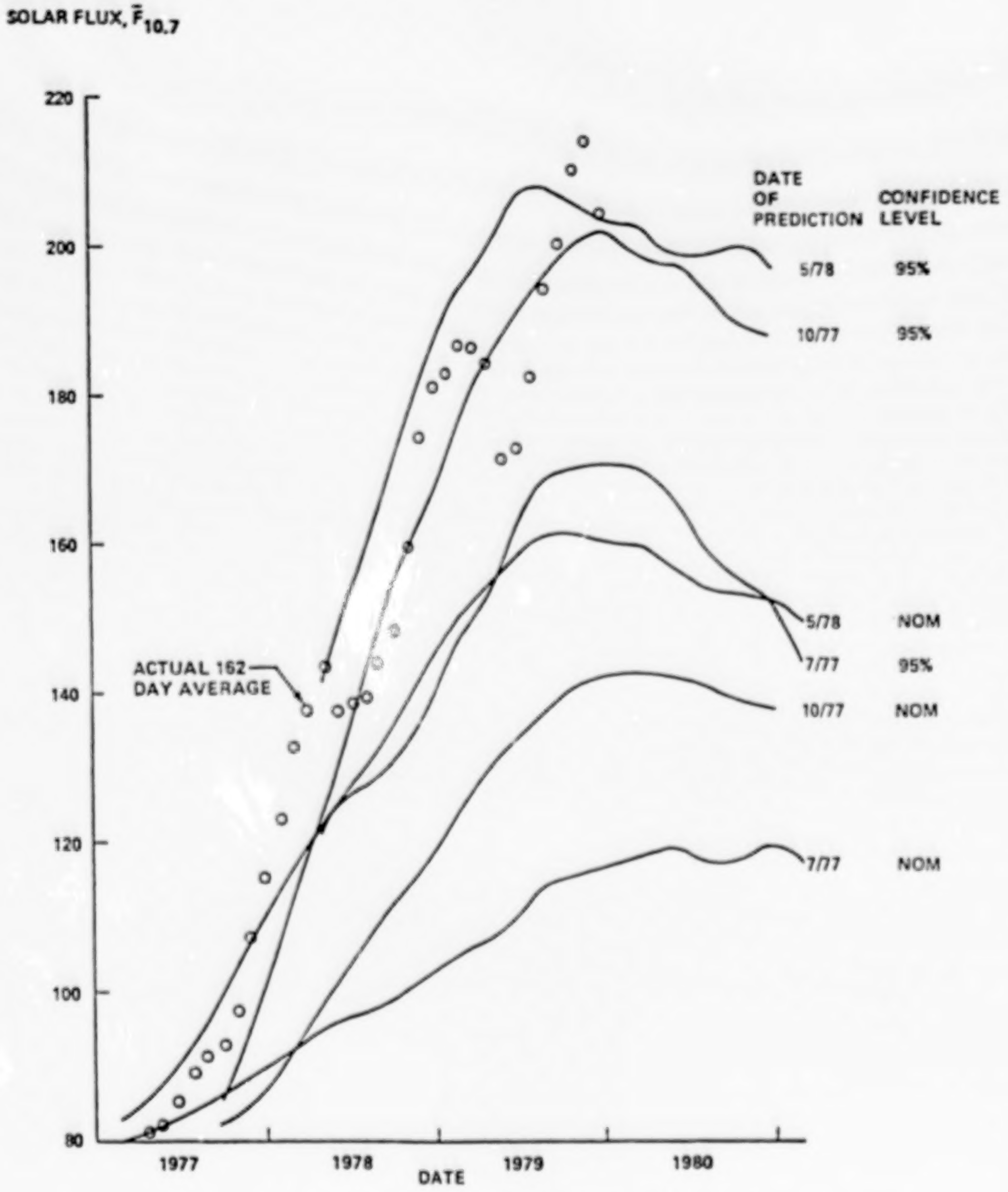
0 SOME POLITICAL/PROGRAMMATIC EFFECTS - $, TIME,
vs IMPACT ON GO AHEAD IF PROJECT WON'T SUCCEED
WITH A CERTAIN PROBABILITY

0 NOMINAL AND ± 2σ ATMOS. VARIATIONS - WHEN AND HOW BIG

0 DAILY VARIATIONS - SPIKES IN ρ, AP, F 10.7



ACTUAL AND PREDICTED SOLAR FLUX



ACTUAL AND PREDICTED SOLAR FLUX

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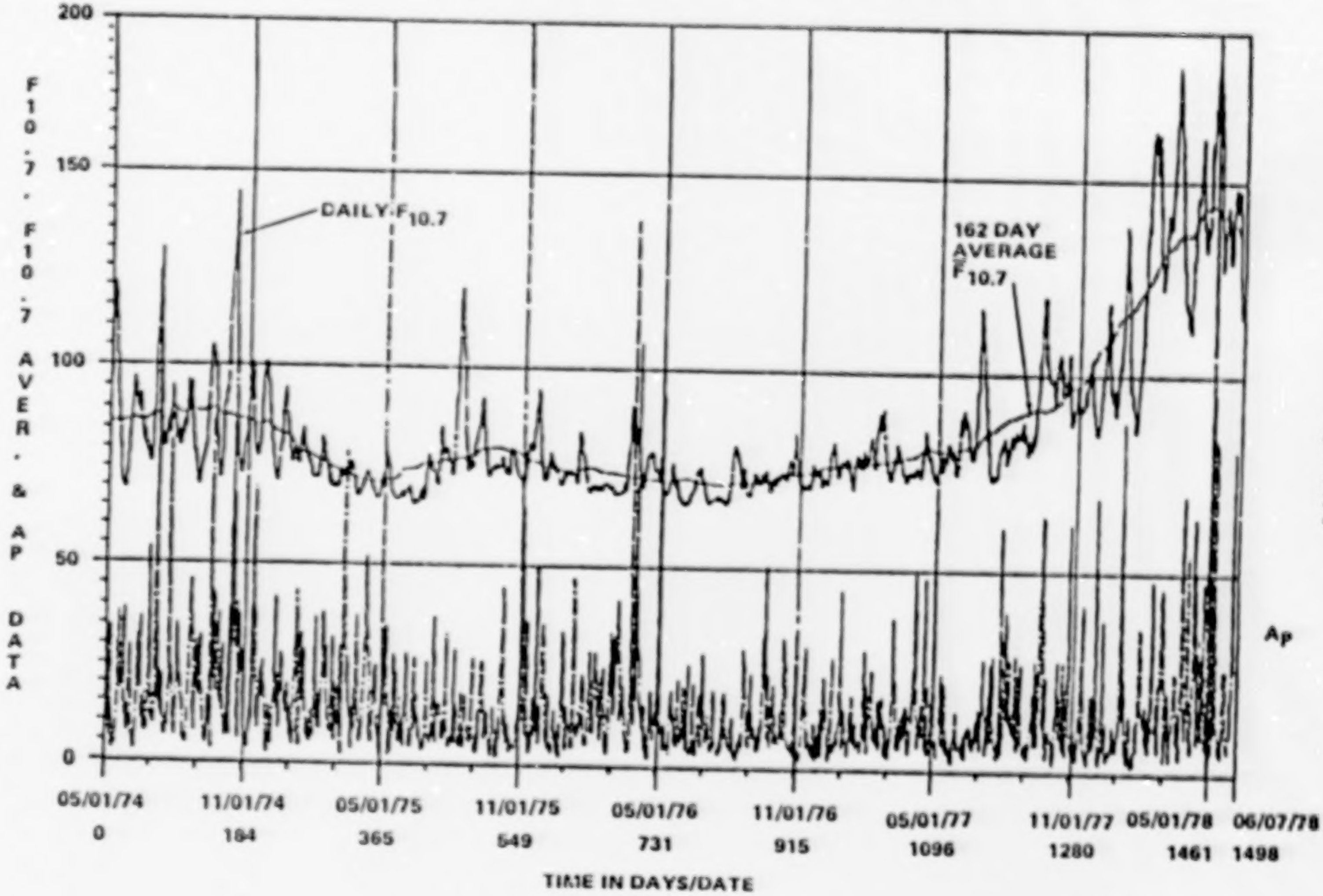

ACTUAL SOLAR ACTIVITY DATA

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00 MISSION PLANNING EFFECTS

0 SKYLAB - SOME INTERESTING NOTES ON LIFETIME

0 SOLAR ACTIVITY - PREDICTIONS - ACTUAL

0 TIMELAGS, BIASES AND FUDGE FACTORS

0 SPACE TELESCOPE AND REACTION WHEEL ASSEMBLY DESIGN - SPIKE IN P, AP ... WHAT TO DO.

0 SPACE STATION - ORBIT MAINT. ORBIT DECAY PREDICTION AND FREQUENCY TO UPDATE

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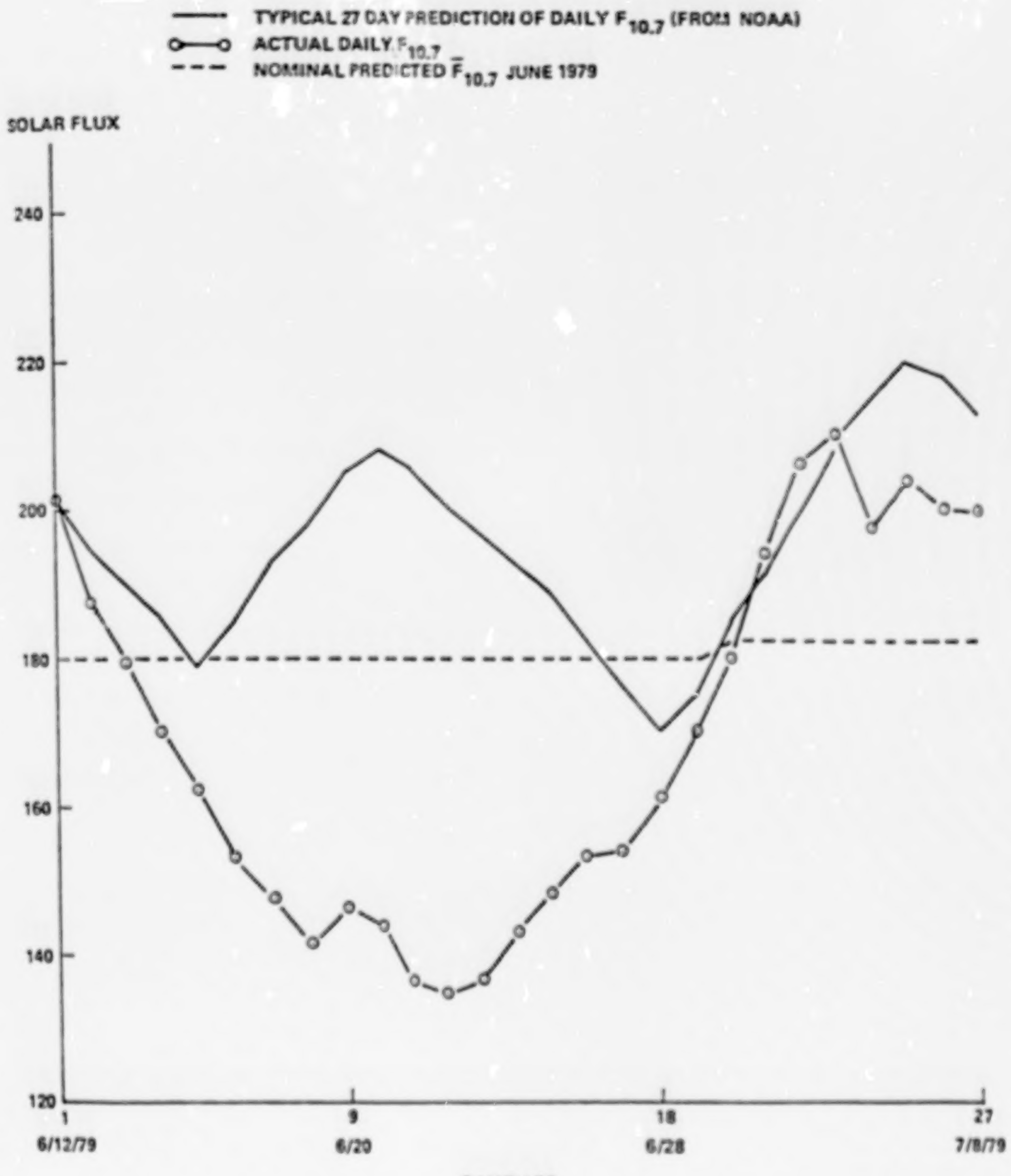
MISSION DESCRIPTION FOR CLUSTER CONFIGURATION AND LIFETIME PREDICTION (SKYLAB)

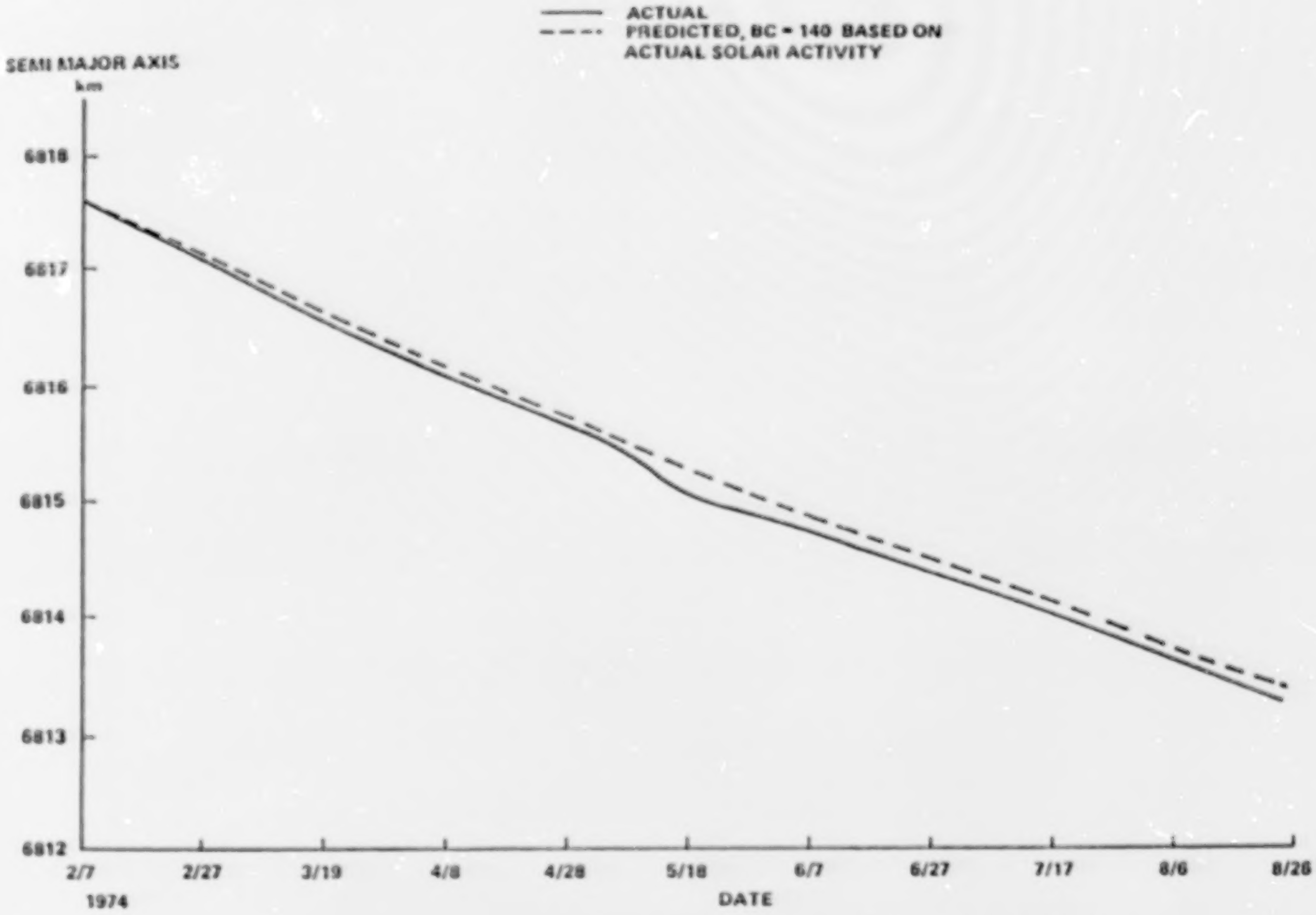
Memorandum Date		9/20/69 (MSFC)		1/20/70 (MSFC)		4/70 (LMSC)		12/2/70 (MSFC)		9/6/72 (MSFC)	
		Time	M/C_DA	Time	M/C_DA	Time	M/C_DA	Time	M/C_DA	Time	M/C_DA
Phase	Configuration	(Days)	(kg/m^2)	(Days)	(kg/m^2)	(Days)	(kg/m^2)	(Days)	(kg/m^2)	(Days)	(kg/m^2)
1	WS	0-2	89.33	0-2	101.6	0-2	115.24	0-1	115.24	Initial	
2	WS + CSM	2-30	106.42	2-29	115.2	2-30	128.83	1-29	128.83	Altitude	
3	WS	30-90	87.10	29-85	99.3	30-90	114.16	29-71	114.16	Maintained	
4	WS + CSM	90-146	103.18	85-140	111.5	90-146	127.84	71-127	127.84	Until End of	
5	WS	146-180	82.32	140-190	95.0	146-180	112.64	127-173	112.64	Manned	
6	WS + CSM	180-236	98.84	190-245	107.4	180-236	126.83	173-229	126.38	Mission	
7	WS	236-Impact	77.64	245-Impact	90.6	236-Impact	111.56	229-Impact	111.56	240-Impact	122.0
Launch Date		3/15/72		3/15/72		7/15/72	11/15/72	11/9/72		4/30/73	
Altitude (nmi)		235		235		235	235	235		235	
Inclination (deg)		35		50		50	50	50		50	
Mass (kg) at end of mission		44826		52317		67962	67962	67962		74558	
Predicted Lifetime Nominal - Days		1660		1760		2093	2070	2074		2360	
Years		4.54		4.82		5.73	5.67	5.68		6.64	
+2σ - Days		1120		1210		1442	1394	1415		1650	
- Years		3.07		3.32		3.95	3.82	3.87		4.52	

SKYLAB LIFETIME (IMPACT) PREDICTIONS DURING THE PASSIVE PERIOD

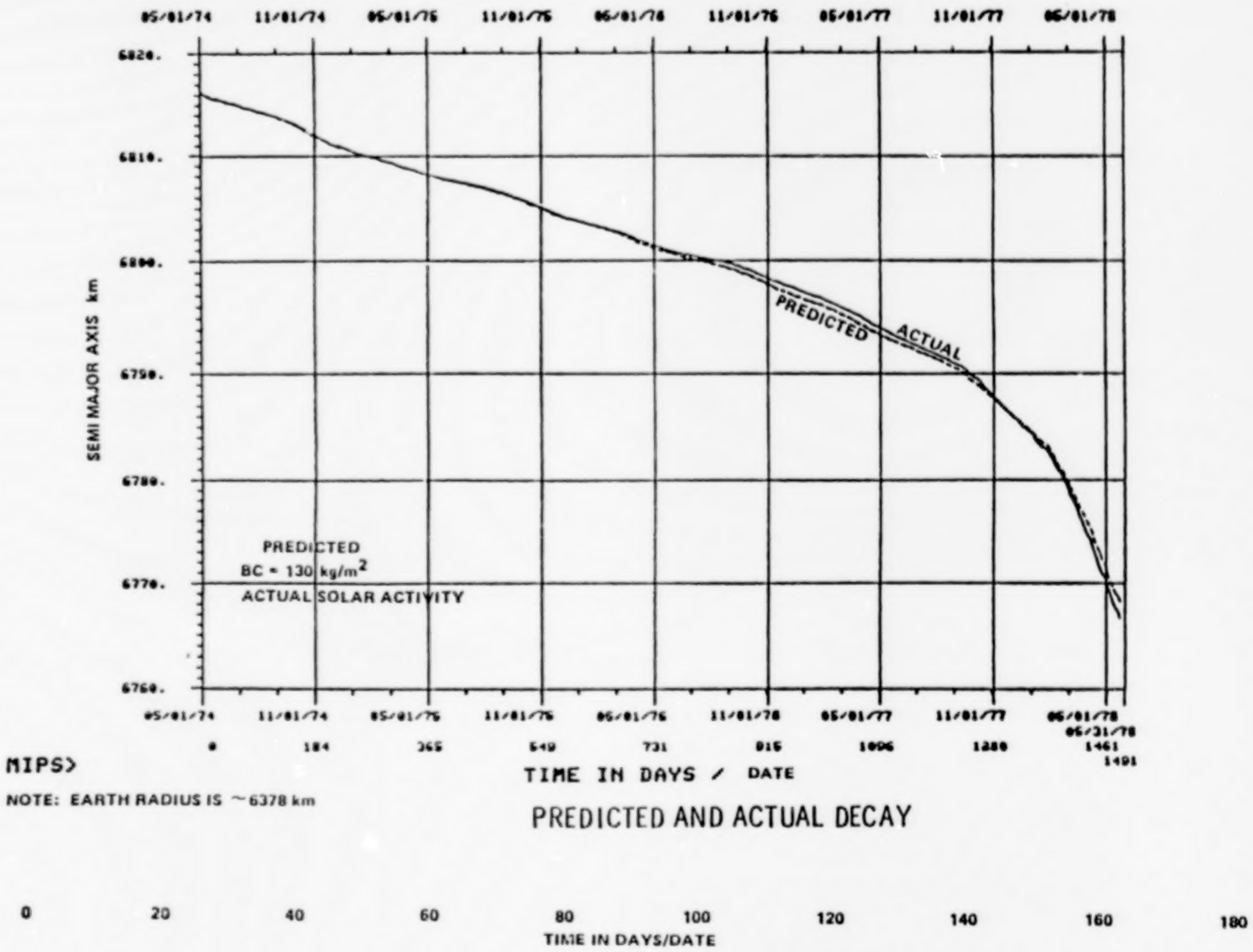
Memo Date	Ballistic Coefficient (kg/m^2)	Predicted Impact (Mo/Yr or Mo/Day/Yr)		
		Nominal	$+2\sigma$	-2σ
Aug. 1, 1973	170	7/81	9/78	10/85
Mar. 11, 1974	207	3/83	11/79	6/92
Sep. 3, 1974	140	5/81	10/78	10/84
Nov. 27, 1974	140	4/81	10/78	6/84
Dec. 12, 1974	140	4/81	10/78	6/84
Feb. 20, 1975	120	1/81	9/78	1/83
May 20, 1975	120	12/80	9/78	11/82
Jul. 27, 1977	144	12/2/80	8/21/79	
Aug. 16, 1977	144	12/7/80	8/23/79	
Oct. 15, 1977	144	4/16/80	5/31/79	
Nov. 18, 1977	144	3/23/80	5/14/79	
Dec. 18, 1977	144	3/14/80	5/22/79	
Feb. 9, 1978	144	12/21/79	5/3/79	
Apr. 10, 1978	144	8/29/79	4/13/79	



COMPARISON OF PREDICTED AND ACTUAL SOLAR FLUX



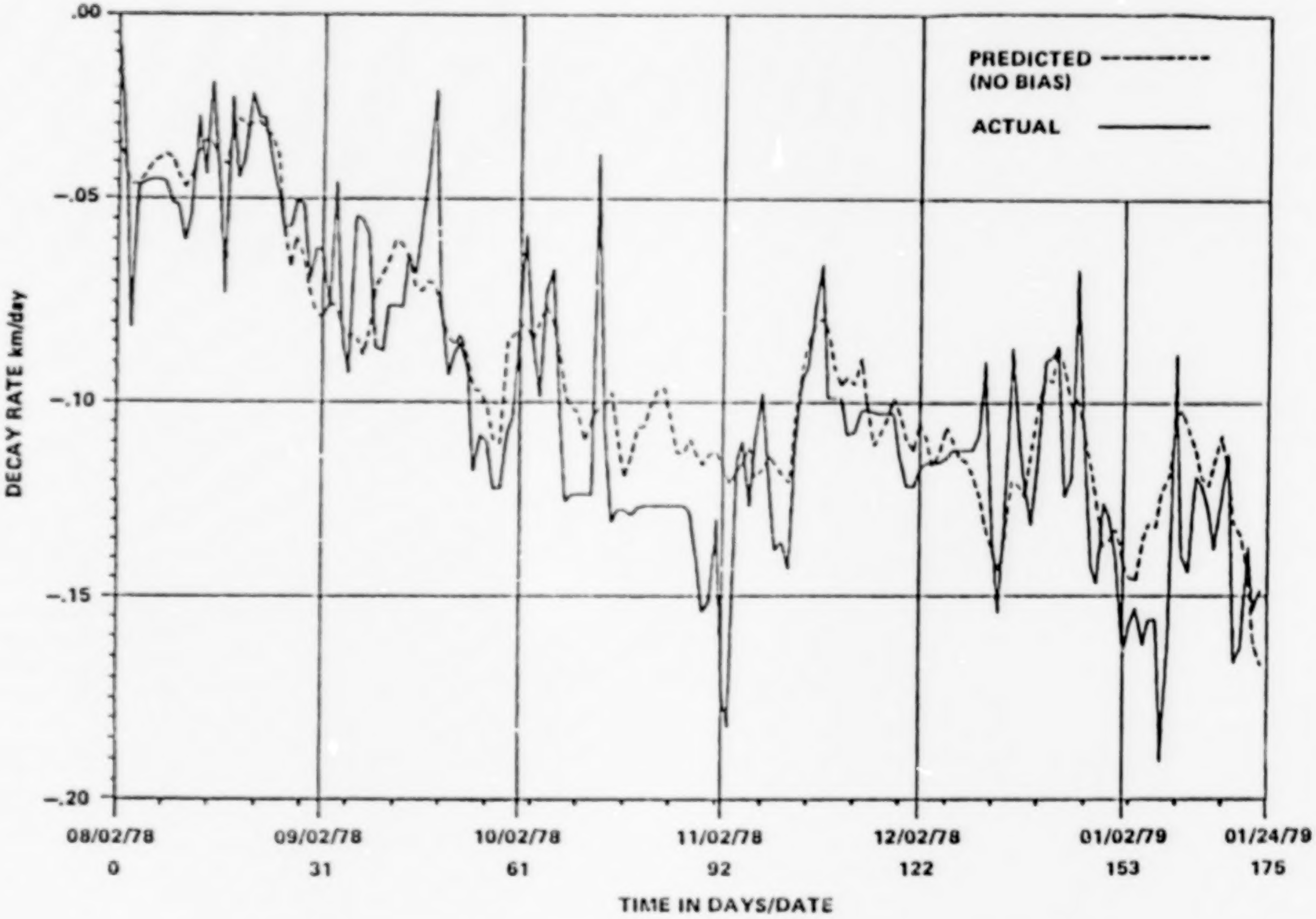
ACTUAL AND PREDICTED DECAY COMPARISON



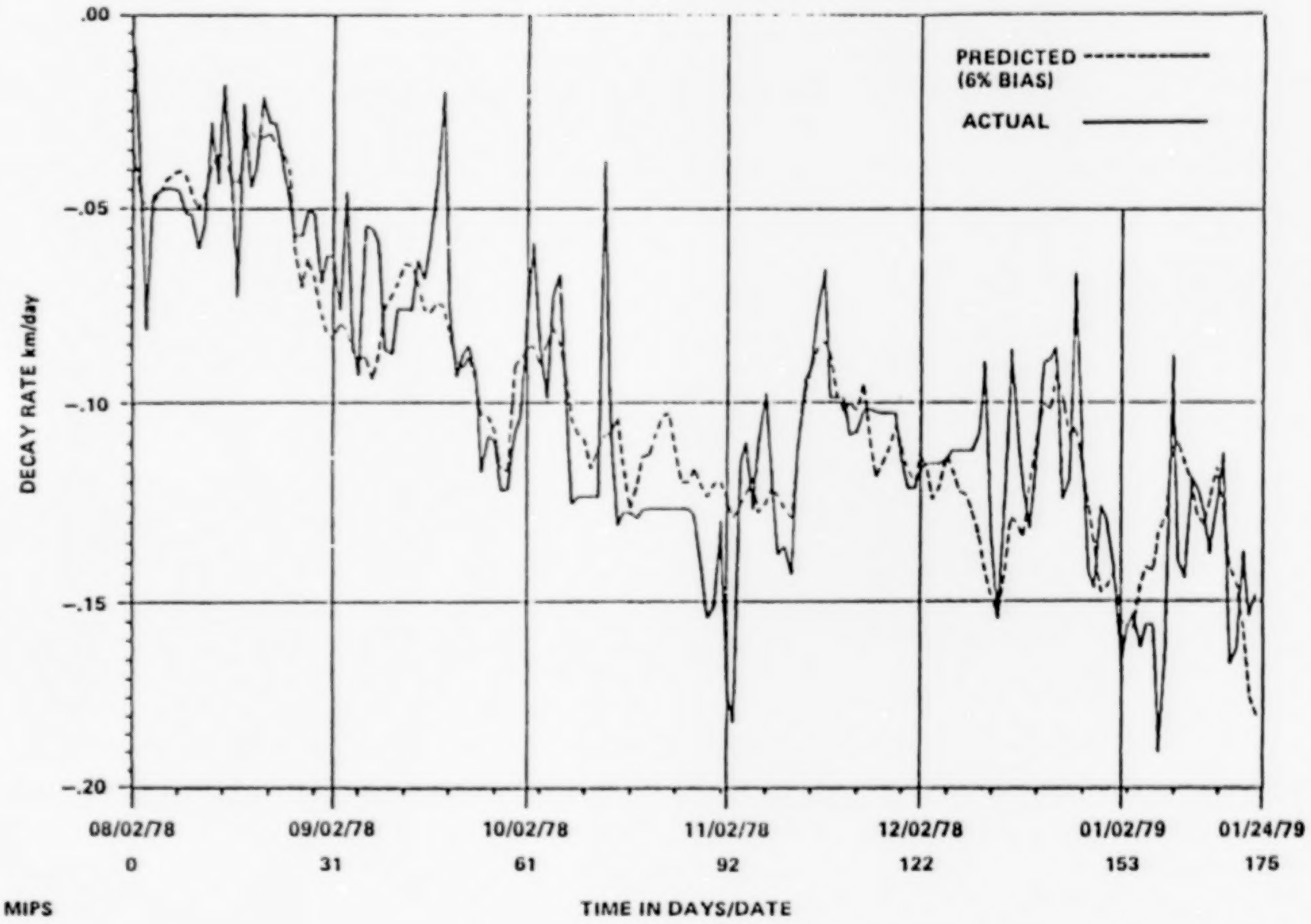
NOTE: EARTH RADIUS IS ~6378 km

PREDICTED AND ACTUAL DECAY

EOVV DECAY COMPARISON USING THEORETICAL BC



EOVV PREDICTED AND ACTUAL DECAY RATES USING THEORETICAL BC



PREDICTED AND ACTUAL DECAY RATES DURING EOVV USING THEORETICAL BC

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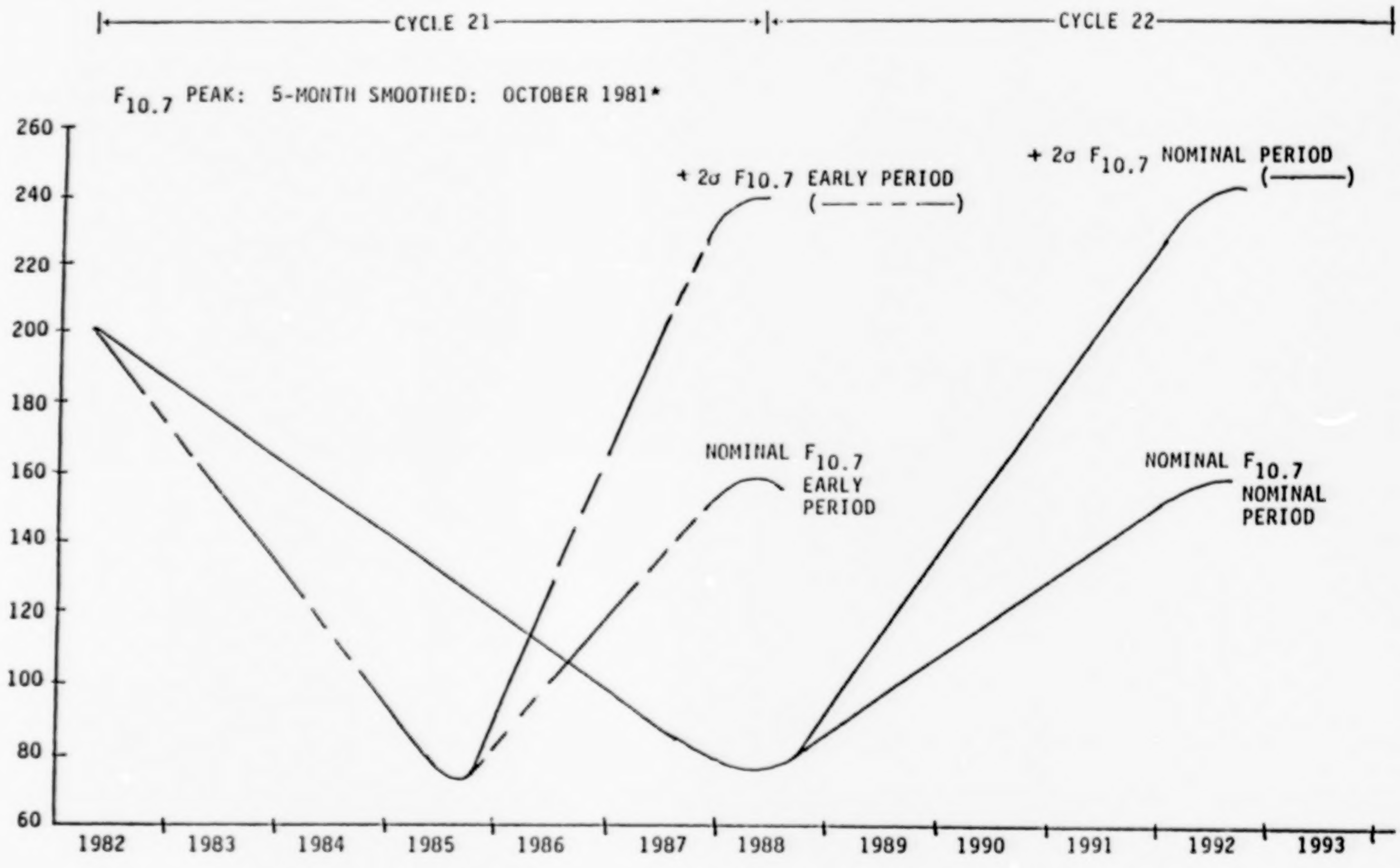
CHART NO.:	STATEMENT ON BIAS IN EL25 ATMOSPHERIC MODEL	DATE: NOVEMBER 18, 1985

O FOR A HIGH RAPIDLY RISING SOLAR ACTIVITY BC APPEARS 5% TO 10% LOWER

O FOR A LOW STEADILY RISING SOLAR ACTIVITY BC APPEARS 5 TO 10% HIGHER



*SUNSPOT PEAK--OCCURRED IN DECEMBER 1979.

ORGANIZATION: EL25	MARSHALL SPACE FLIGHT CENTER SPACE TELESCOPE/REACTION WHEEL ASSEMBLY DESIGN	NAME: G. WITTENSTEIN
CHART NO.:		DATE: NOVEMBER 18, 1985

- O TWO MAJOR PROBLEMS
  - O WHEEL SPEED AND CONTROL
  - O JITTER AND SCIENCE QUALITY

M.E. LAW SENSITIVITY RESULTS
V2 POP

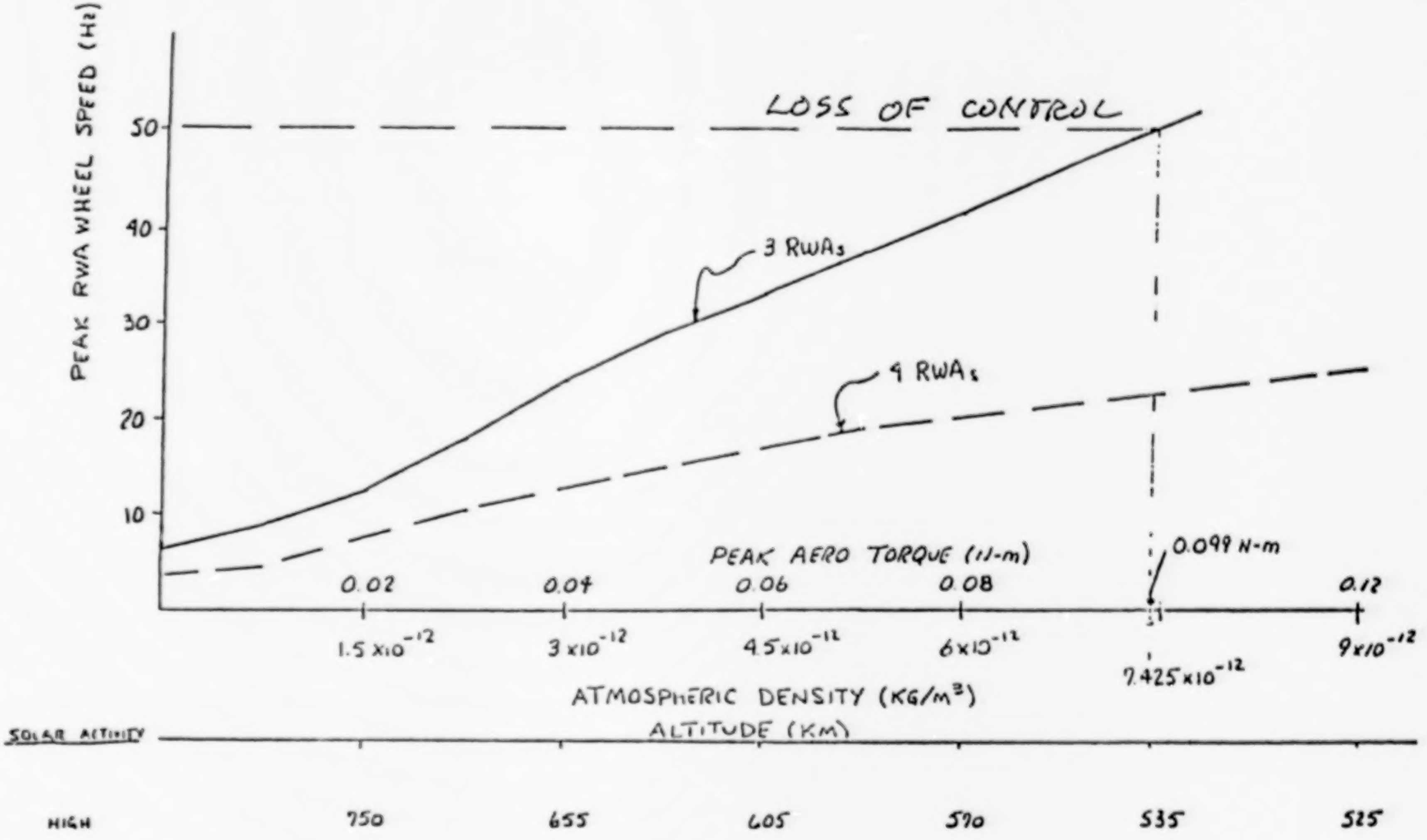


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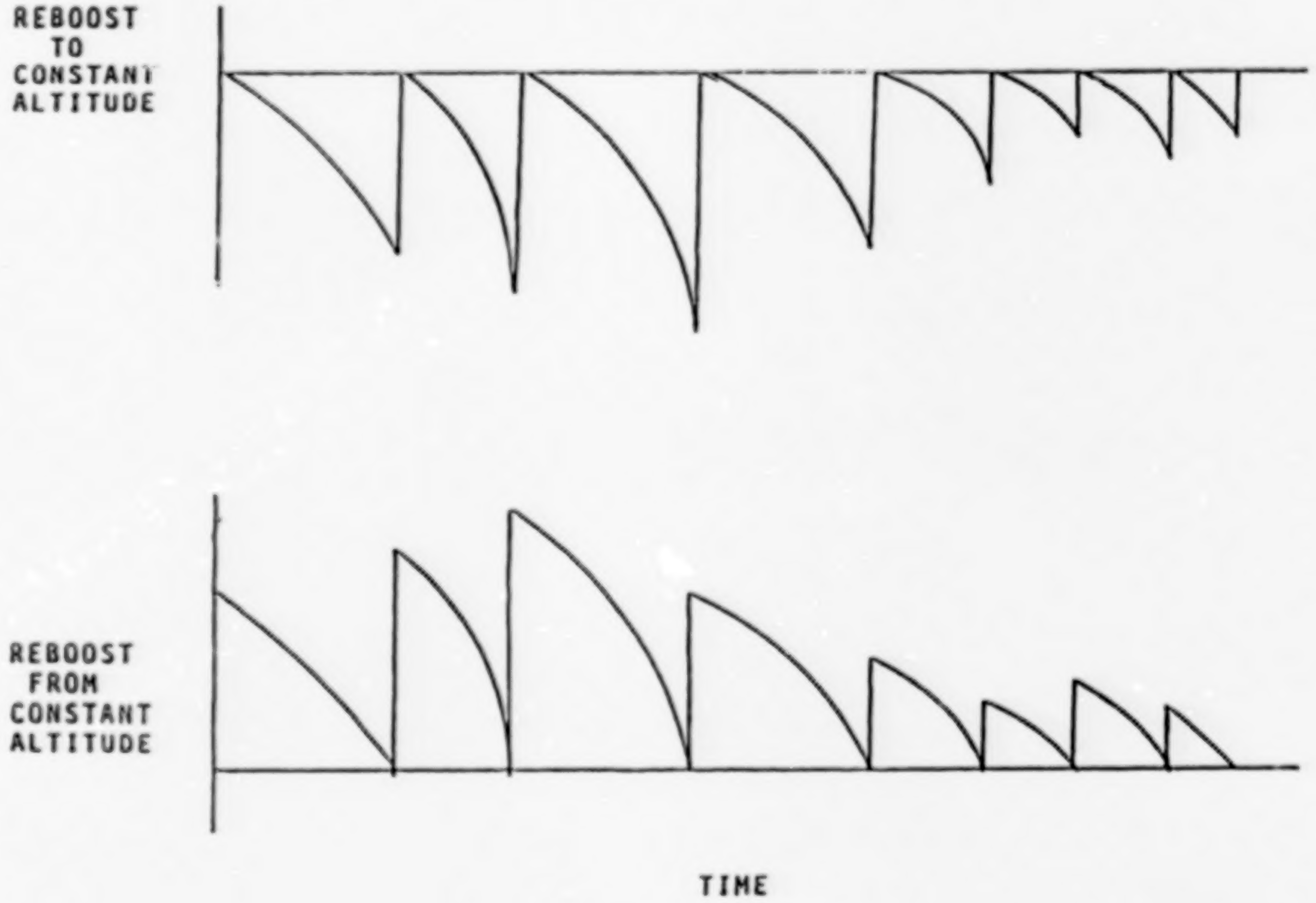
CHART NO.:	ORBITAL LIFETIME APPLICATIONS	DATE: NOVEMBER 18, 1985

ORBITAL LIFETIME APPLICATIONS

FOR LOW ORBIT EARTH SATELLITES SUCH AS THE PLANNED MANNED SPACE STATION REBOOST WILL BE NECESSARY TO PROVIDE THE LONG DURATION LIFETIME. THESE PERIODIC REBOOSTS COULD BE DONE WITH A PROPULSIVE VEHICLE OR THE SPACE STATION COULD HAVE ITS OWN SYSTEM FOR REBOOST. ESTIMATES HAVE BEEN MADE OF THE PROPELLENT REQUIRED FOR REBOOST FOR LEVELS OF SOLAR ACTIVITY AS SHOWN BELOW.

SOLAR ACTIVITY	SUNSPOT NUMBER	PROPELLENT REQUIRED IN POUNDS EACH YEAR
LOW	50	1,000
MEDIUM	100	3,000
HIGH	200	10,000

ORGANIZATION: EL23	MARSHALL SPACE FLIGHT CENTER	NAME: V. L. BUCKELEW
CHART NO.:	REBOOST PROFILES	DATE: AUGUST 1985



ORGANIZATION: EL25	MARSHALL SPACE FLIGHT CENTER SATELLITE LIFETIME	NAME: G. WITTENSTEIN
CHART NO.:		DATE: NOVEMBER 18, 1985

SUMMARY

SOLAR ACTIVITY EFFECT ON ATMOSPHERIC DENSITY PLAYS A MAJOR ROLE IN

- o MISSION PLANNING
- o SATELLITE/SPACECRAFT DESIGN, COST AND OPERATION
- o EXPERIMENT OPERATIONAL QUALITY
- o BAD PRESS

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DENSITY UNCERTAINTY EFFECT ON COST OF SPACE STATION REBOOST

Walter Unterberg and Claus Meisl, Rockedyne International

Summary:

If the Space Station is designed for operation in a nominal atmosphere for ten years and the atmosphere is two- sigma higher than nominal during the entire ten year period, the impact would be an additional cost of $70.1 million, based on a resupply cost of $3200/lb.

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DENSITY INFLUENCE ON SPACE STATION PROPULSION

- DENSITY DATA FROM NASA - MSFC
- 500 KM (270 N.MI) ALTITUDE
- 10 YR PERIOD STARTING 1992
- REFERENCE CONFIGURATION REBOOST
- 440 SEC SPECIFIC IMPULSE FOR O_2 / H_2

ATMOSPHERE	ATMOSPHERIC DENSITY, $KG.M^{-3}$	90-DAY REBOOST TOTAL IMPULSE, LB_F .SEC	90-DAY O_2/H_2 PROPELLANT REQUIREMENT, LBM
MAXIMUM OF +20	35×10^{-13}	483,000	1100
10-YR AVG. OF +20	16×10^{-13}	224,000	509
MAX. OF NOMINAL	11×10^{-13}	151,000	348
10-YR AVG. OF NOM.	4.5×10^{-13}	62,000	141
MAXIMUM OF -20	3.7×10^{-13}	51,000	116
MINIMUM OF -20, NOM., +20	0.8×10^{-13}	11,000	25

10 YEAR PROPELLANT RE-SUPPLY LIFE CYCLE COST

- TANK MASS = ½ PROPELLANT MASS
- RESUPPLY COST = \$3200/LB.

+20 (10 YR. AVG)	\$ 97.7 MILLION
NOM. (10 YR. AVG)	27.6 MILLION
	\$ 70.1 MILLION

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SPACE STATION MOMENTUM MANAGEMENT

V. Buckalew, Miriam Hopkins, NASA/Marshall Space Flight Center

Gravity gradient stabilization is planned for the space station. Torques arise from air-drag since the center of pressure is not the same as the center of mass of the satellite. The magnitude of these torques varies depending upon the orientation of the solar panels. Adjustments are made through the use of CMG's (Control Moment Gyros). In time, if the CMG's saturate, torque must be bled off using thrusters; however, that is undesirable because it expends propellant and contaminates the local environment. The task of the engineer is to design the CMG's to handle the aerodynamic torques and design the configuration of the spacecraft to prevent, if possible, CMG saturation. For this application the long-term atmospheric density trends are of less importance than the rate of change of density within an orbit. In principle CMG's could be designed for the worst case of maximum solar activity, but the penalty for overdesign is excess mass and cost.

In summary, present models are inadequate for this application with the greatest need being a reliable prediction of maximum rates-of-change of density within an orbit.

WORKSHOP ON UPPER AND MIDDLE ATMOSPHERIC DENSITY

MODELING REQUIREMENTS FOR SPACECRAFT DESIGN AND OPERATIONS

SPACE STATION CONTROL

M. HOPKINS
CONTROL SYSTEMS DIVISION
SYSTEMS DYNAMICS LABORATORY
MSFC
NOVEMBER 1985

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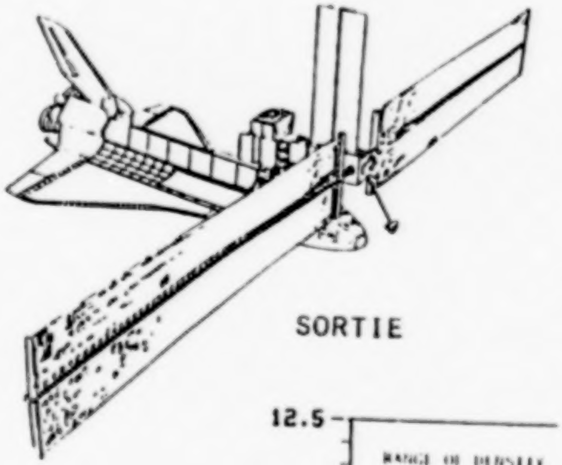
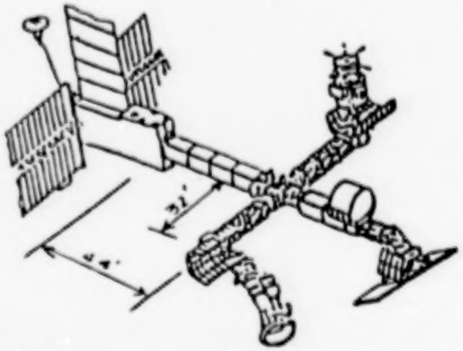
SPACE STATION CONTROL

BACKGROUND

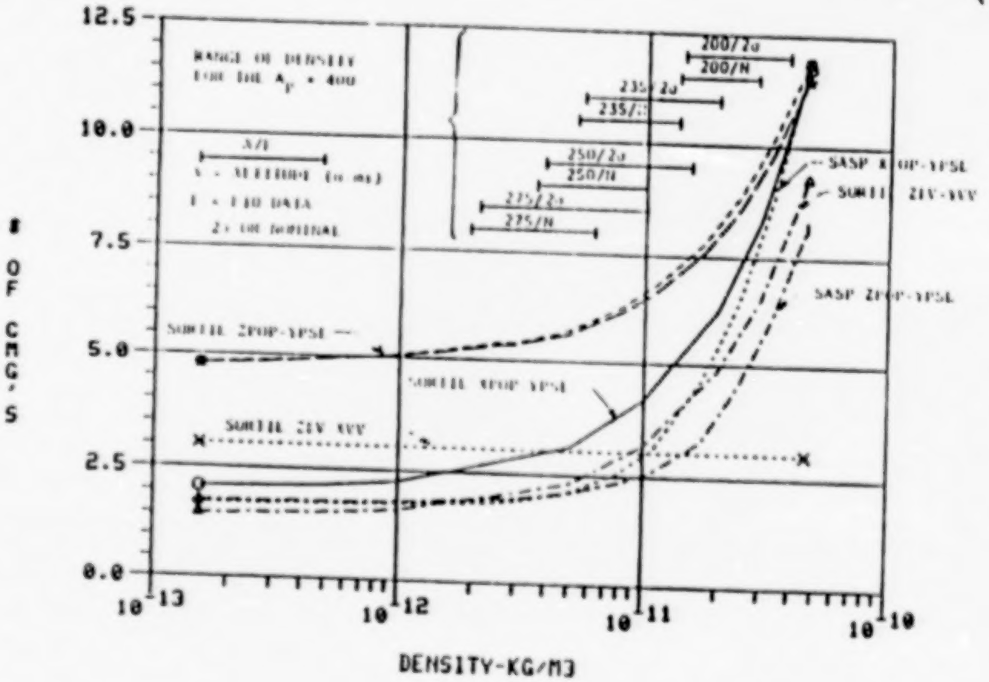
- WITH ADVENT OF LARGE AREA SPACECRAFT IN LOW EARTH ORBIT, AERODYNAMIC TORQUE BECOMES A DOMINANT DISTURBANCE.
    - CONFIGURATION
    - ATTITUDE REQUIREMENTS
    - DESIGN DENSITY
        - MAGNITUDE
        - PROFILE
- AERODYNAMIC DOMINANCE EXEMPLIFIED BY CONTROL REQUIREMENT ANALYSES FOR 25Kw SPACE PLATFORM.
    - CMG SIZING REQUIREMENTS VERY NEARLY PROPORTIONAL TO DESIGN DENSITY.



SORTIE



SCIENCE AND APPLICATION SPACE PLATFORM (SASP)



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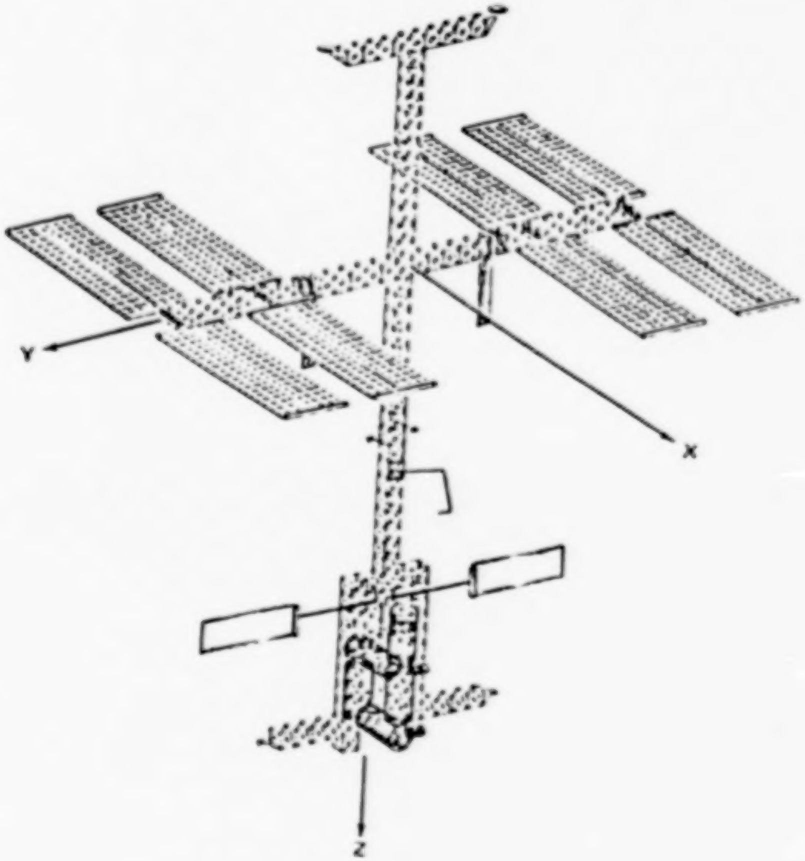
SPACE STATION CONTROL



SINGLE KEEL SPACE STATION

- o BASELINE ATTITUDE FOR SPACE STATION HAS LONGITUDINAL AXIS EARTH POINTING WHILE SOLAR ARRAYS REMAIN SUN POINTING.
- o BOTH AERODYNAMIC AND GRAVITY GRADIENT TORQUES VARY AS ARRAYS ROTATE.
- o MOMENTUM MANAGEMENT SCHEME SEEKS MINIMUM TORQUE AVERAGE ATTITUDE.

SPACE STATION CONTROL

- TO PREVENT CMG SATURATION, ESTIMATE OF DESIRED TILT ANGLES REQUIRED DURING BUILDUP.

- PAYLOAD COMMUNITY MAY REQUIRE ORBITS/DAYS AT CONSTANT ATTITUDE.

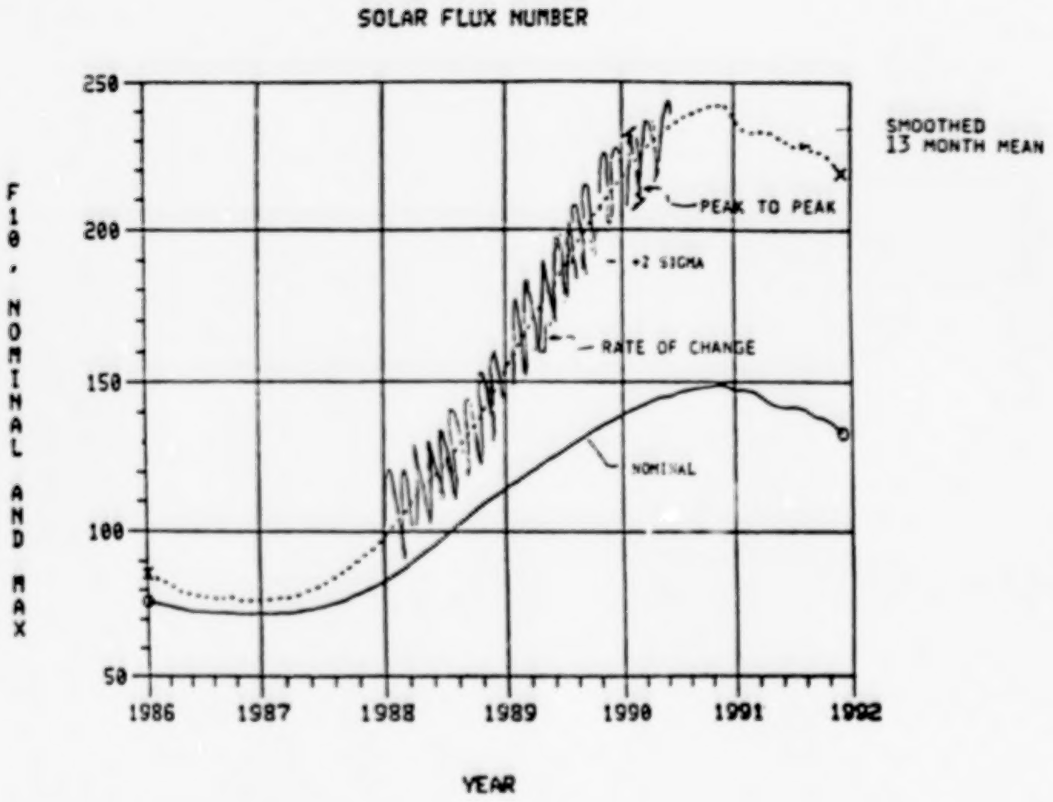
- HOW WELL DOES ATMOSPHERE MODEL REFLECT DAY TO DAY VARIATIONS?

- CONTROL SIMULATIONS USE MSFC/J70 ATMOSPHERIC DENSITY MODEL.

BASELINE INPUT

$F_{10.7} = \bar{F}_{10.7} = 230$

$A_p = 140$



CONTROL DESIGNER IS

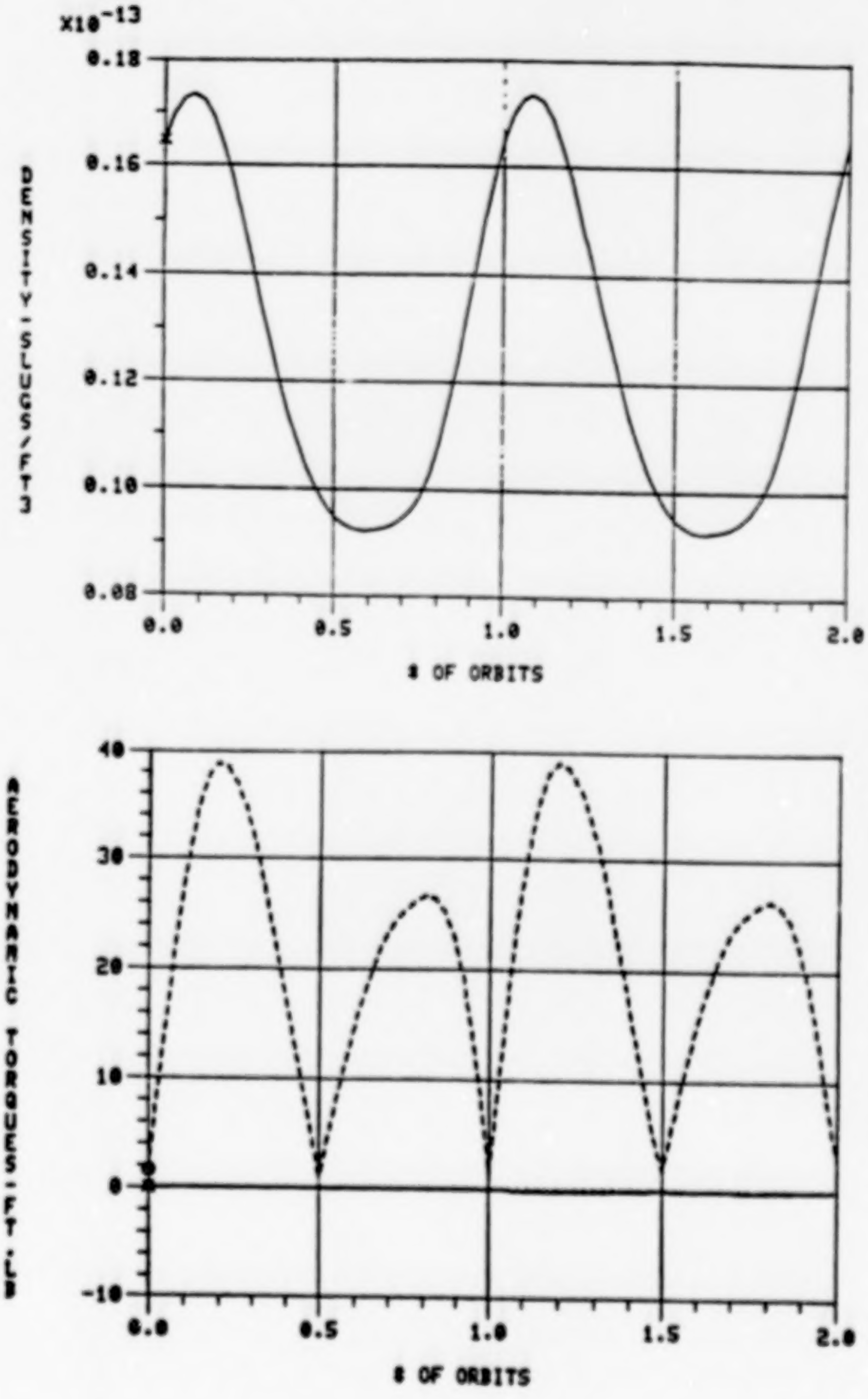
- o NOT CONCERNED WITH 13 MONTH SMOOTHED MEAN (AT LEAST DIRECTLY).
- o THE SMOOTHED MEAN PLUS THE PEAK TO PEAK VARIATION DICTATE SYSTEM SIZING REQUIREMENTS AND ESTIMATES TO USERS OF PROBABLY TILT ANGLES OFF NOMINAL ATTITUDE.
- o RATE OF CHANGE OF DENSITY ON A PER ORBIT BASIS IS THE PRIMARY CONCERN. DICTATES THE ROBUSTNESS REQUIRED. GENERALLY NEED TO KNOW ONLY THE MAX VALUE.
- o OTHERWISE DESIGNER IS RELATIVELY INSENSITIVE TO THE DIFFERENCE BETWEEN THE MODEL AND THE ACTUAL DENSITY ON A DAY BY DAY BASIS.

SPACE STATION CONTROL

THE FOLLOWING SERIES OF CHARTS WILL ILLUSTRATE

- o DENSITY ENCOUNTERED AND RESULTING AERODYNAMIC TORQUES FOR A REFERENCE CASE.
- o OUT-OF-PLANE (OP) AND IN PLANE (IP) TILT ANGLES DETERMINED BY MOMENTUM MANAGEMENT SCHEME AND RESULTING MOMENTUM.
- o COMPARISON OF MOMENTUM STORAGE REQUIREMENTS WITH AND WITHOUT ACTIVE SCHEME.
- o CHANGE IN TILT ANGLE REQUIREMENT FOR TWO STATIC CONDITIONS OF DENSITY.
- o SYSTEM PERFORMANCE DURING HYPOTHITICAL MAGNETIC STORM WHERE AVERAGE DENSITY INCREASES WITH TIME.
- o MOMENTUM STORAGE REQUIREMENTS WITHOUT ONBOARD ADAPTIVE MOMENTUM MANAGEMENT.

TYPICAL DENSITY AND AERODYNAMIC PROFILES



$F_{10.7} = \bar{F}_{10.7} = 230$

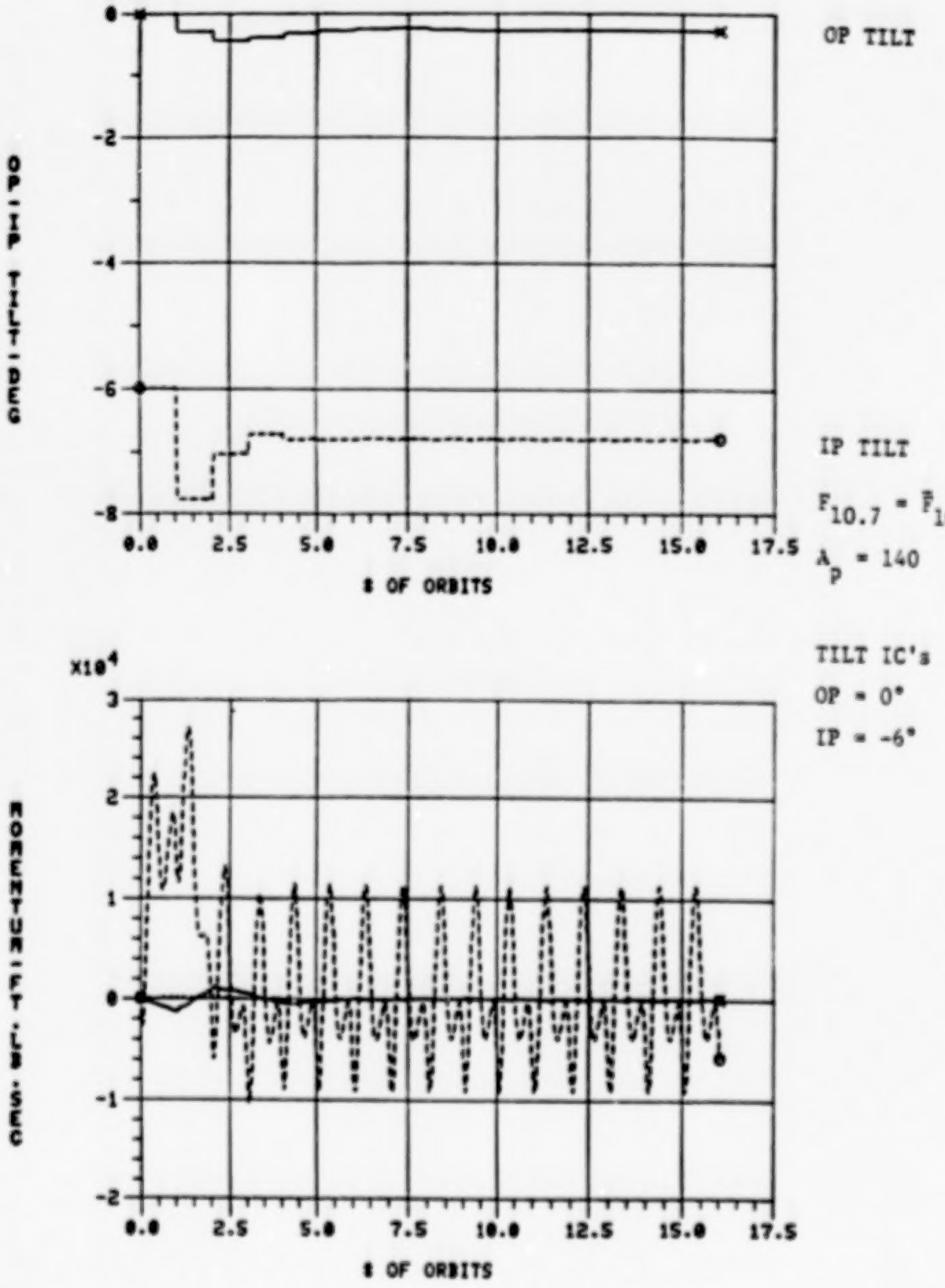
$A_p = 140$

TILT IC's

OP = 0°

IP = -6°

TILT ANGLES AND RESULTING MOMENTUM



$F_{10.7} = \bar{F}_{10.7} = 230$

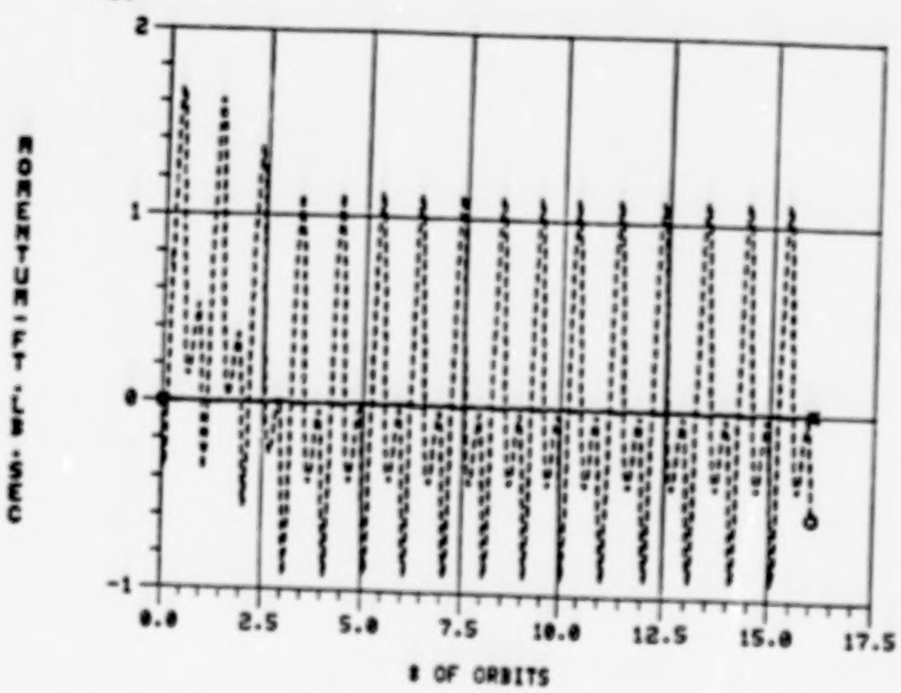
$A_p = 140$

TILT IC's

OP = 0°

IP = -6°

MOMENTUM REQUIREMENTS WITH AND WITHOUT ACTIVE CONTROL



WITH ACTIVE CONTROL

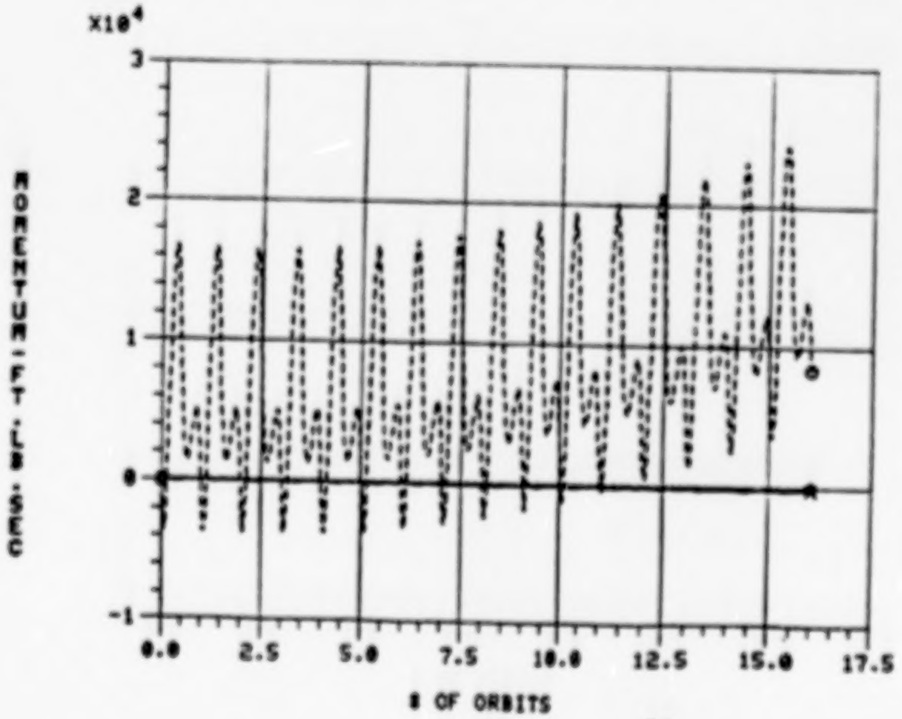
$F_{10.7} = \bar{F}_{10.7} = 230$

$A_p = 140$

TILT IC's

OP = -.30°

IP = -6.8°



WITHOUT ACTIVE CONTROL

EFFECT OF DAILY SOLAR FLUX INCREASE

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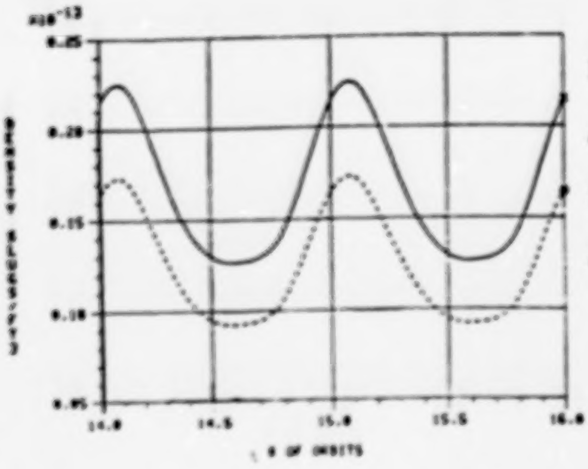
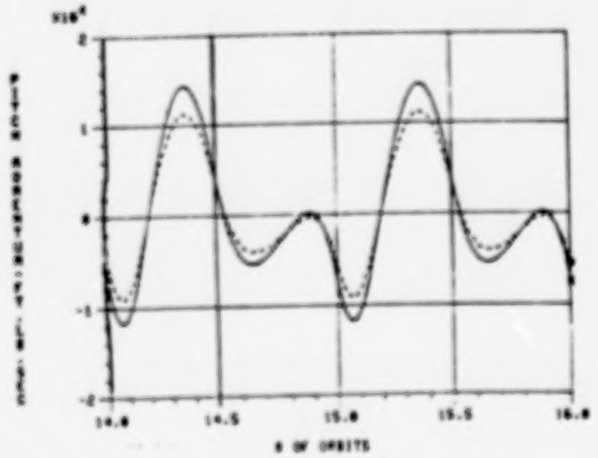


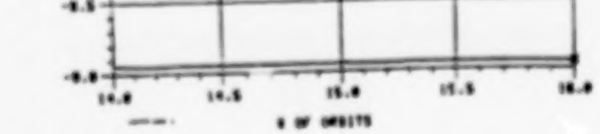
$F_{10.7}$ = 315, $\bar{F}_{10.7}$ = 230

A_p = 140

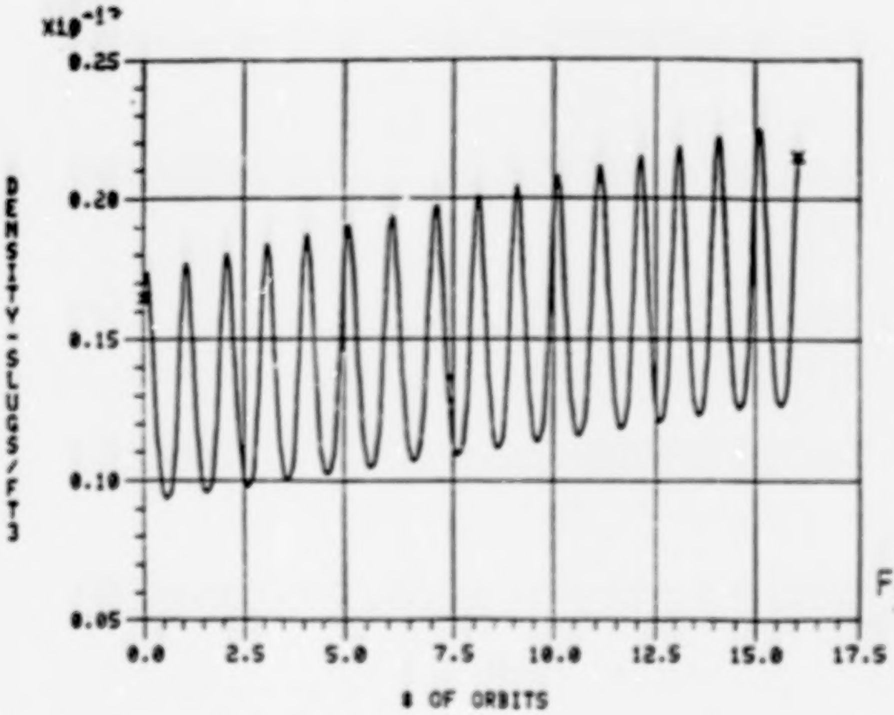
$F_{10.7}$ = $\bar{F}_{10.7}$ = 230

A_p = 140



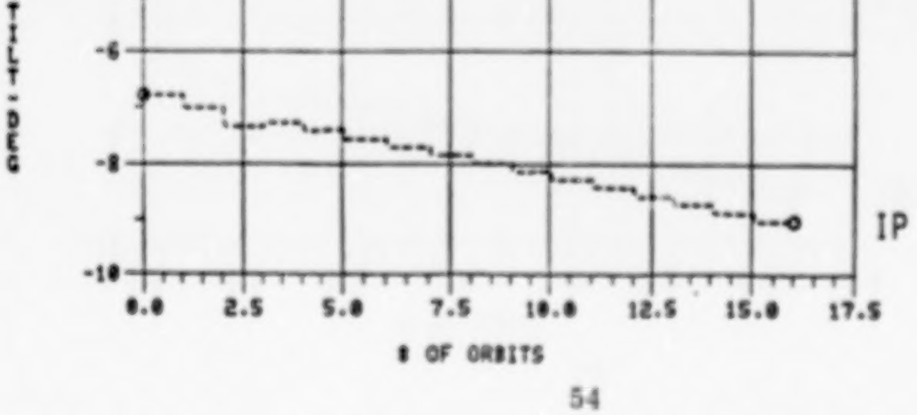


EFFECT OF GEOMAGNETIC ACTIVITY INCREASE



$F_{10.7} = \bar{F}_{10.7} = 230$
A_p = 140 TO 400 OVE
15 ORBIT PERIOD

TILT IC's
OP = -.3°
IP = -6.8°



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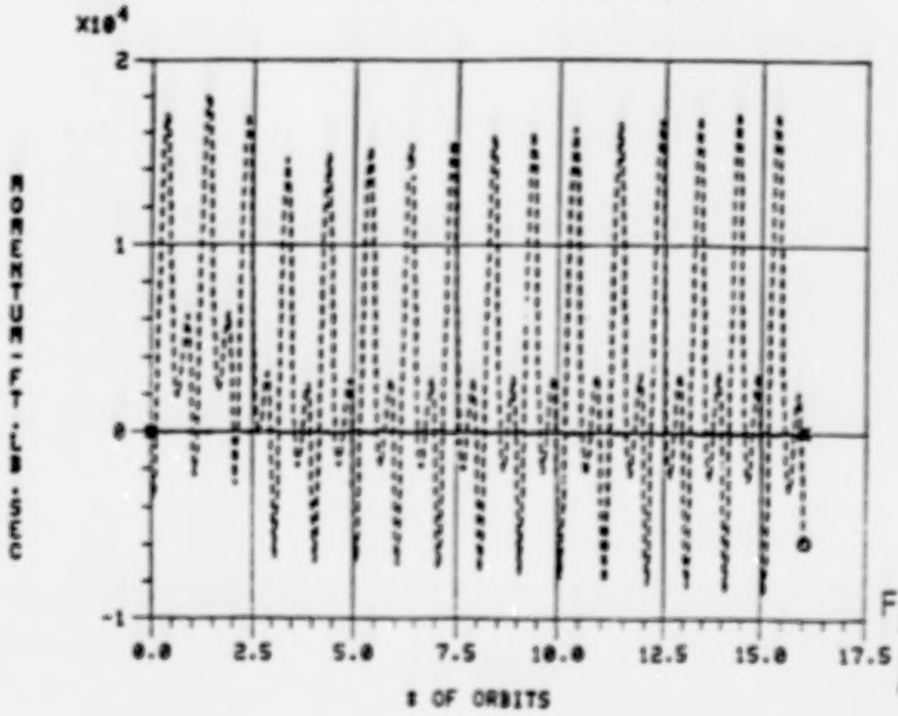
MOMENTUM CHANGES DUE TO INCREASE IN GEOMAGNETIC ACTIVITY

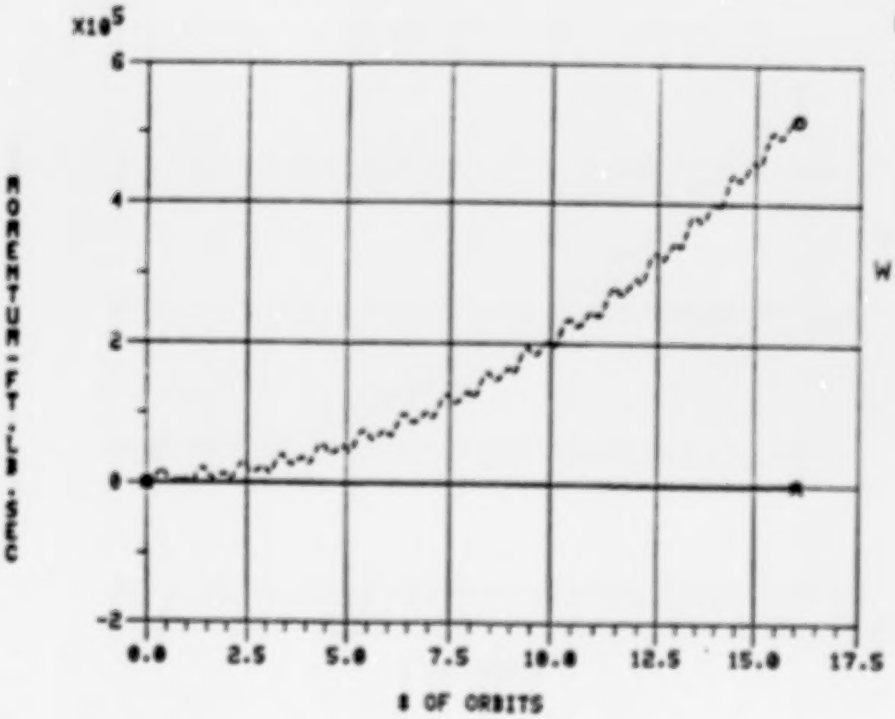


WITH ACTIVE CONTROL

$F_{10.7} = \bar{F}_{10.7} = 230$

A_p = 140 TO 400 OVER
15 ORBIT PERIOD

TILT IC's
OP = -.3°
IP = -6.8°



WITHOUT ACTIVE CONTROL

SPACE STATION CONTROL

SUMMARY

- o CONTROL REQUIREMENTS FOR SPACE STATION AND ASSOCIATED PLATFORMS HEAVILY INFLUENCED BY AERODYNAMIC TORQUES.
- o DEGREE OF SENSITIVITY IS COMBINATION OF CONFIGURATION, ATTITUDE REQUIREMENTS AND ATMOSPHERIC DENSITY.
- o AERODYNAMIC TORQUES FOR CURRENT DUAL KEEL SPACE STATION REDUCED BECAUSE OF SMALLER MOMENT ARM.

CONCERN

- SPACE STATION CONTROL SYSTEM REQUIREMENTS DEPEND ON TRANSIENT EFFECT OF DENSITY. CURRENT MODEL DOES NOT REFLECT THESE TRANSIENTS BUT RELIES ON MAGNIFICATION OF STEADY STATE ATMOSPHERE TO COVER EVERYTHING. AN ATMOSPHERIC DENSITY MODEL WHICH INCLUDES TRANSIENT EFFECTS IS NEEDED.

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SPACE STATION CONTROL MOMENT GYRO CONTROL

Aldo Bordano, NASA/Johnson Space Center

The potential large center-of-pressure to center-of-gravity offset of the Space Station makes the short term, within an orbit, variations in density of primary importance.

The large range of uncertainty in the prediction of solar activity will penalize the Space Station design, development, and operation.

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SPACE STATION CMG CONTROL

NOVEMBER 19, 1985
MPAD/FM4
ALDO BORDANO
ET AL.

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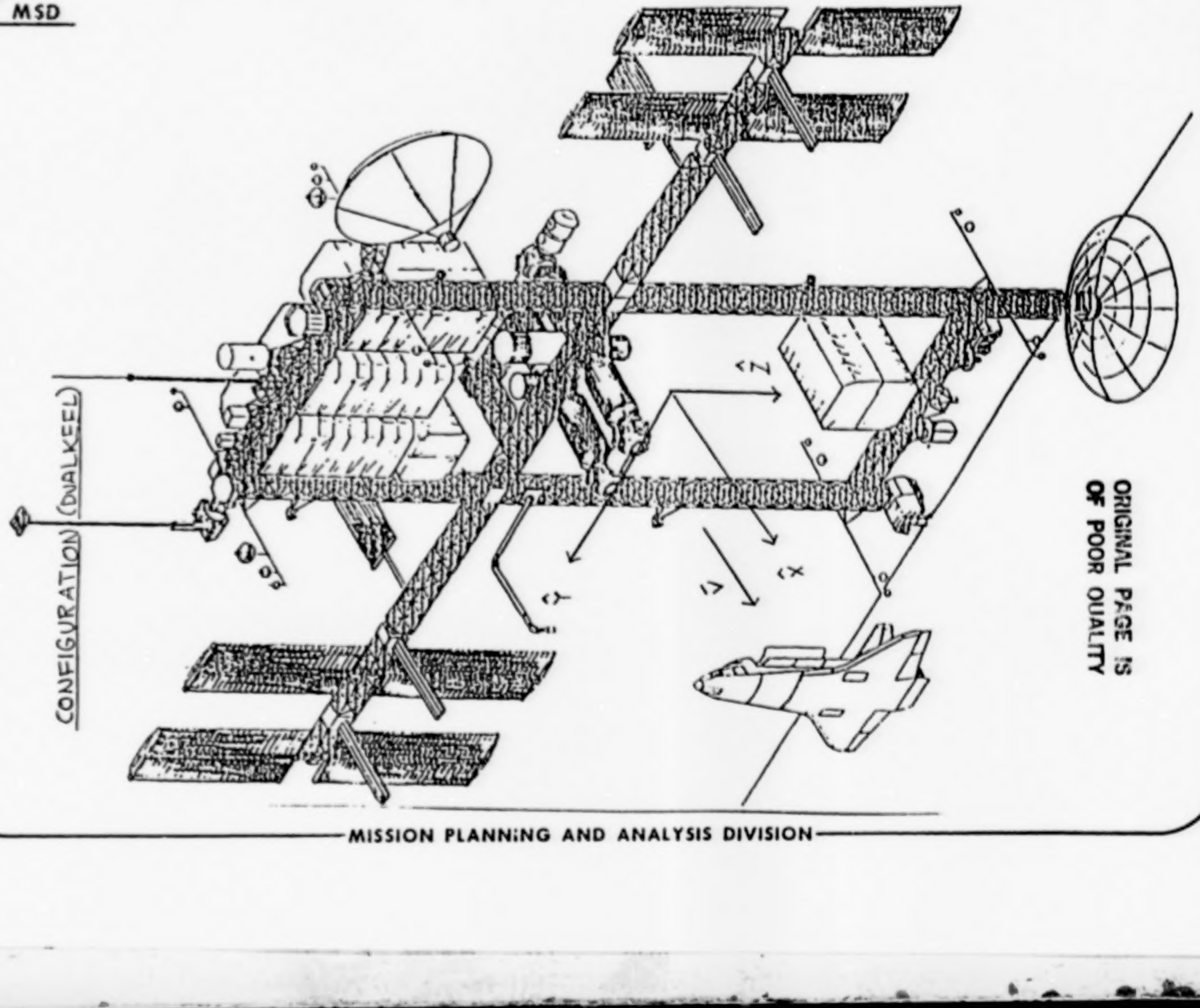
- CURRENT STUDY INTEREST AND EFFORTS
  - CMG CONTROL SYSTEM SIZING *
  - DUAL KEEL MOMENTUM SENSITIVITIES *
  - MOMENTUM MANAGEMENT STRATEGIES AND SUPPORTING ALGORITHM DEVELOPMENT

*DATA PACKAGES INCLUDED FOR HARRY BUCHANAN

NASA MISSION SUPPORT DIRECTORATE **JSC**

MSD



CONFIGURATION (DUALKEEL)

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MISSION PLANNING AND ANALYSIS DIVISION

- CONFIGURATION (CONT.)

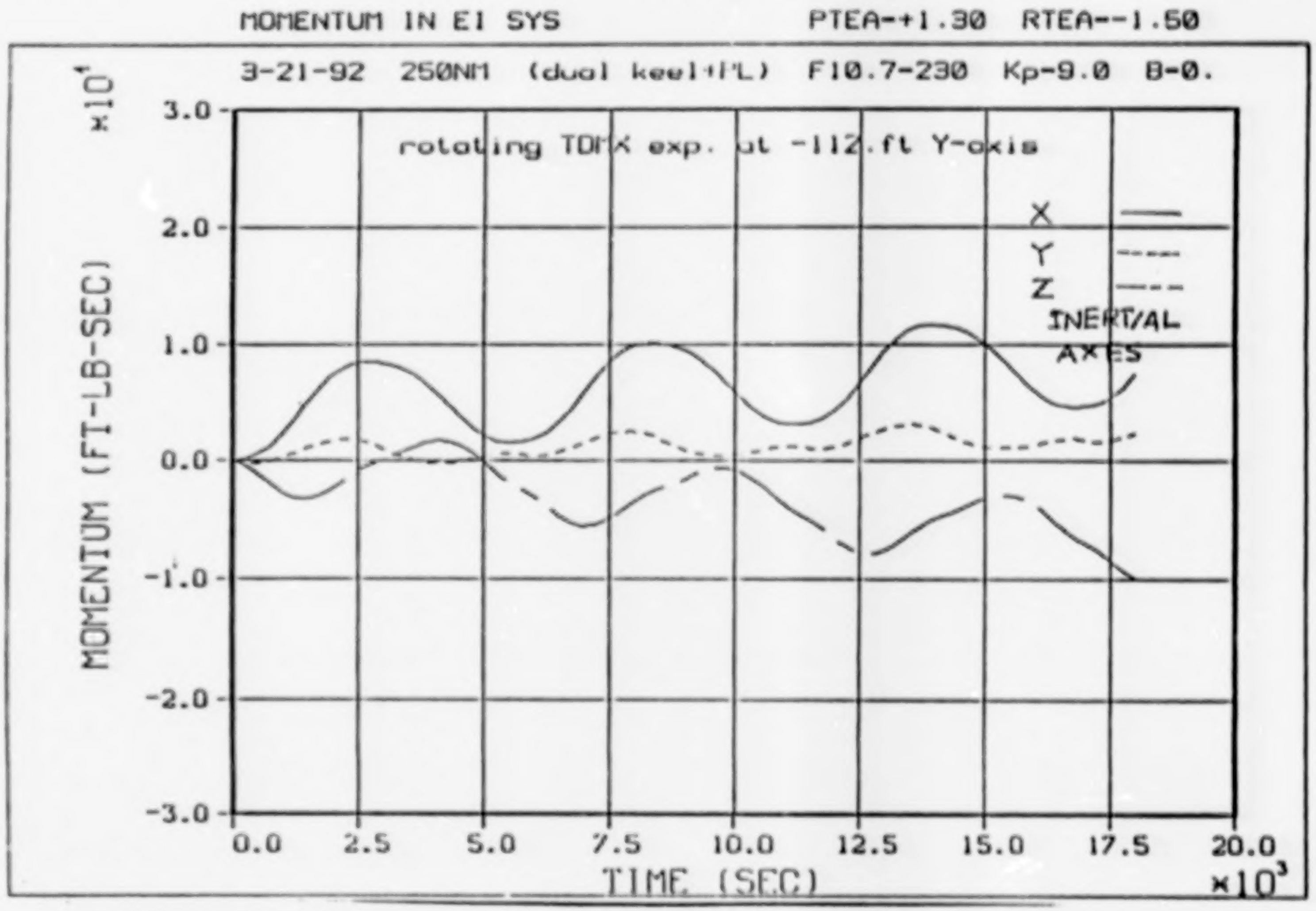
POWER TOWER + PL & SERVICING				DUAL KEEL + PL			
WEIGHT	- 452007 LB			WEIGHT	- 580162 LB		
INERTIAS	IXX	1.8900E8	SLG-FT^2	INERTIAS	IXX	1.4060E8	SLG-FT^2
	IYY	1.8522E8			IYY	1.0897E8	
	IZZ	8.4067E6			IZZ	5.7214E7	
	IXY	6.9866E4			IXY	1.0580E6	
	IXZ	-8.7079E5			IXZ	6.5741E5	
	IYZ	-3.9985E5			IYZ	1.2931E6	
CG	XCG	-.88671	FT	CG	XCG	-24.45463	FT
	YCG	-1.13342			YCG	-5.011408	
	ZCG	143.5007			ZCG	- 1.022853	
CP	XCP	≈ 0.0	FT		XCP	≈ -13.65645	FT
	YCP	≈ 0.0			YCP	≈ -29.48985	
	ZCP	≈ 0.0			ZCP	≈ -31.20042	

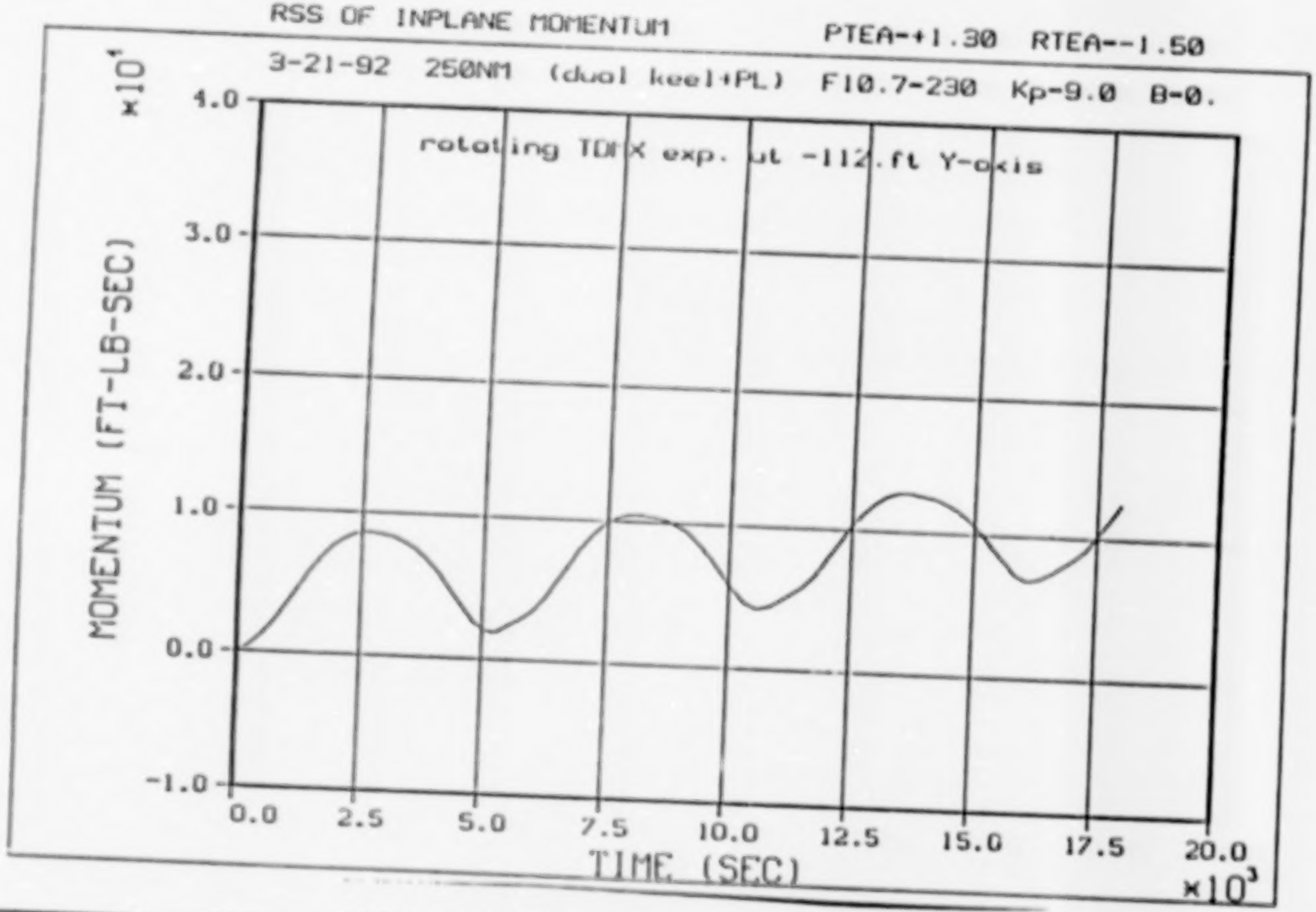
COORDINATE SYSTEM REFERENCE - GEOMETRIC CENTER OF TRANSVERSE BOOM

- CMG SIZING KEY POINTS
  - POWER TOWER (IOC)
    - OUT-OF-ORBIT PLANE MOMENTUM WAS THE REQUIREMENT DRIVER DUE TO A LARGE CP. TO CG. OFFSET IN THE STATION X AXIS (> 100 FT.)
    - PITCH TEA WAS EMPLOYED TO REDUCE THE OUT-OF-ORBIT PLANE MOMENTUM

- CMG SIZING KEY POINTS (CONT)
  - DUAL KEEL (IOC)*
    - IN-ORBIT PLANE MOMENTUM WILL BE THE REQUIREMENT DRIVER DUE TO A POTENTIAL
    - LARGE CP. TO CG. OFFSET IN THE STATION Y AXIS (> 30 FT.)
    - ROLL TEA REDUCES IN-PLANE MOMENTUM SOMEWHAT
    - SOLAR DYNAMIC EXPERIMENT CONTRIBUTES LARGELY TO THE IN-PLANE MOMENTUM
      - LARGE AREA (~ 2400 FT^2)
      - LOCATED NEAR END OF UPPER BOOM (-112 FT.)

*NOT NECESSARILY CONFIGURATION OPTIMAL FOR CMG SIZING OR MOMENTUM MANAGEMENT


MOMENTUM IN EI SYS
PTEA-+1.30 RTEA--1.50
3-21-92 250NM (dual keel+PL) F10.7-230 Kp-9.0 B-0.
rotating TDMX exp. at -112.ft Y-axis
X
Y
Z
INERTIAL AXES
MOMENTUM (FT-LB-SEC)
x10^1
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
TIME (SEC)
x10^3



RSS OF INPLANE MOMENTUM PTEA-+1.30 RTEA--1.50

3-21-92 250NM (dual keel+PL) F10.7-230 Kp-9.0 B-0.

rotating TDRX exp. at -112.ft Y-axis

- MOMENTUM MANAGEMENT KEY POINTS
  - SECULAR CHANGES CAN BE RELATIVELY LARGE (~ 2500 FT-LB-SEC PER ORBIT, FOR STEA)
  - IMPLIES FREQUENT, IF NOT CONTINUOUS, IN-PLANE MOMENTUM DUMPING WITH REASONABLY LARGE ROLL ANGLES (> .5 DEG) ABOUT ROLL TEA
  - MANEUVER MOMENTUM MUST BE SUFFICIENT FOR REQUIRED MOMENTUM DUMPING ($I\Delta\omega$ = 5000 FT-LB-SEC, $\Delta\omega$ = .002°/SEC)

DUAL KEEL CONFIGURATION, CIR, ORBIT ALT. = 250 N.MI., B = 0, 3-21-92.
STEA - SHORT TERM EXTREME ATMOSPHERE F10.7 = 230, KP = 9.

- NATURAL ENVIRONMENT EFFECTS
  - PEAK IN-PLANE MOMENTUM SENSITIVITY TO NATURAL ENVIRONMENT PARAMETERS

	PEAK IN-PLANE MOMENTUM (NO SECULAR CHANGE INCL.)	
F 10.7 = 150, KP = 3	~1200	FT-LB-SEC
150, KP = 7	~2500	
150, KP = 9	~5000	
F 10.7 = 230, KP = 3	~3000	
230, KP = 7	~4200	
230, KP = 9	~7000	← STEA
F 10.7 = 300, KP = 9	~10000	

  - WIDE RANGE OF MOMENTUM REQUIREMENT RANGING FROM AVERAGES TO EXTREMES OF NATURAL ENVIRONMENT PARAMETERS

DUAL KEEL CONFIGURATION, CR, ORBIT ALT. = 250 N.MI. B = O, 3-21-92

- NATURAL ENVIRONMENT QUESTIONS
  - QUALIFICATION AND PREDICTIVE ACCURACY OF THE JACCHIA MODEL TO THE SPACE STATION FLIGHT ENVELOPE (INCL. ≈ 28.5°, ALT ≈ 210 - 270 N. MI.) RELATIVE TO
    - SHORT TERM CONTROL SYSTEM ANALYSIS (ORBIT TO ORBIT)
    - APPLICATION OF SOLAR FLUX AND GEOMAGNETIC INDEX PARAMETERS
  - UNCERTAINTY OF THE PREDICTED SOLAR CYCLE ENVELOPE IN THE DESIGN TIME FRAME

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HUBBLE SPACE TELESCOPE

G. Nurre, NASA/Marshall Space Flight Center

The Hubble Space Telescope will employ magnetic torque controllers, which make use of the earth's magnetic field augmented by four reaction wheels. DC torques are easily allowed for, but variations, orbit by orbit, can result in excessive wheel speeds which can excite vibratory modes in the telescope structure. If the angular momentum from aerodynamic sources exceeds its allocation of 100 Nms, the excess has to come out of the maneuvering budget since the total capacity of the momentum storage system is fixed at 500 Nms. This would mean that maneuvers could not be made as quickly, and this would reduce the amount of science return.

In summary, there is a definite need for a model that accurately portrays short term (within orbit) variations in density for use in angular momentum management analyses. It would be desirable to have a simplified model that could be used for planning purposes; perhaps applicable only over a limited altitude range (400-700 km) and limited latitude band.

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THE EFFECTS OF ATMOSPHERIC DENSITY ON THE ST PCS

ST PCS DESCRIPTION

EFFECTS OF THE EARTH'S ATMOSPHERE

RECOMMENDATIONS FOR DENSITY MODELING

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THE EFFECTS OF ATMOSPHERIC DENSITY ON THE ST PCS

ST PCS REQUIREMENTS

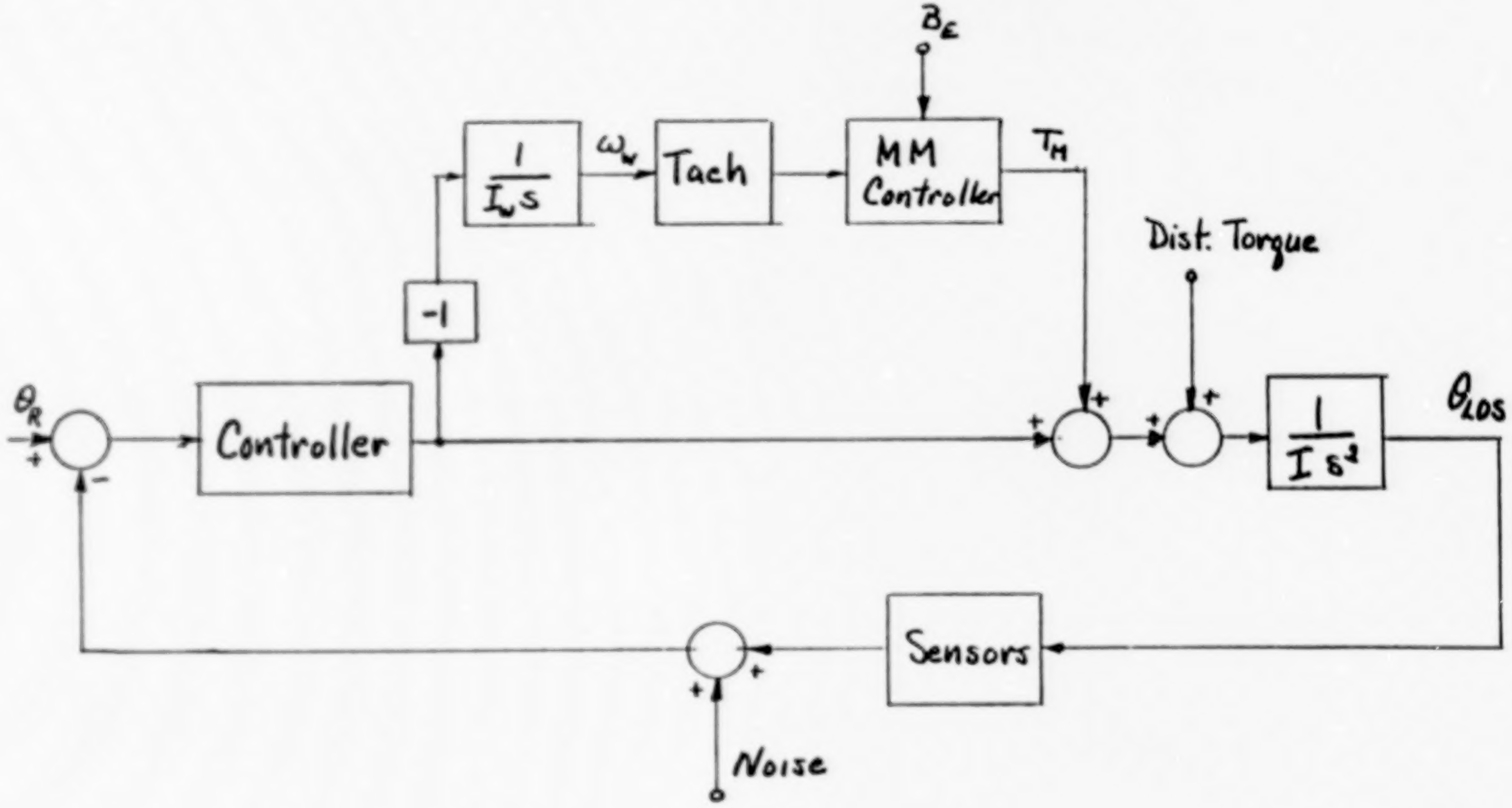
POINTING STABILITY	0.007 $\hat{s}$ RMS
POINTING ACCURACY	0.01 $\hat{s}$ (1σ)

MANEUVER 90° IN 20 MINUTES

AUTONOMOUS OPERATION

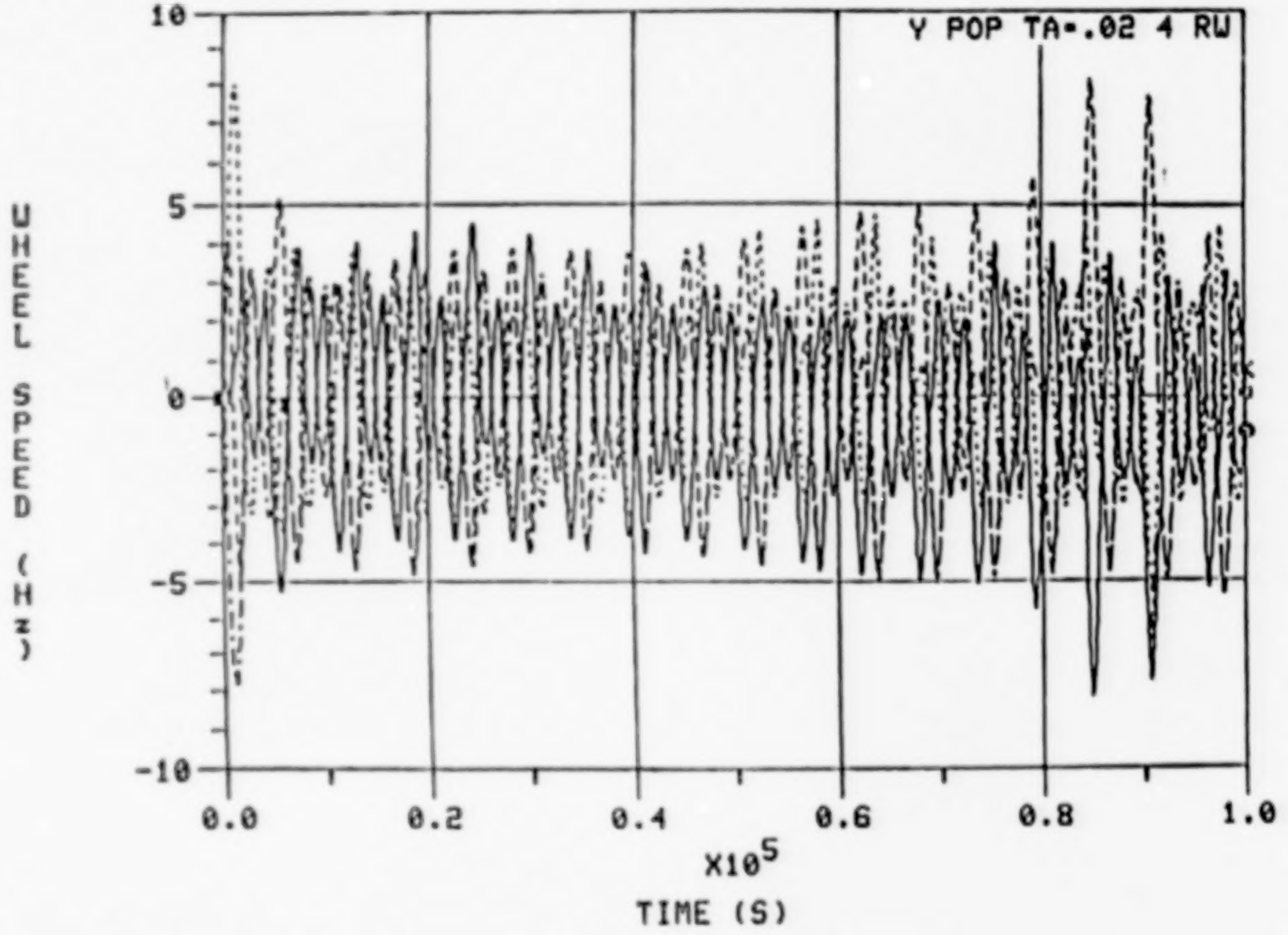
INITIAL ORBITAL ALTITUDE - 593 KM

LAUNCH DATE AUGUST-SEPTEMBER 1986


B_E
$\frac{1}{I_w s}$
ω_w
Tach
MM Controller
T_H
Dist. Torque
-1
θ_R
+
-
Controller
+
+
+
+
$\frac{1}{I s^2}$
θ_{LOS}
Sensors
+
+
Noise

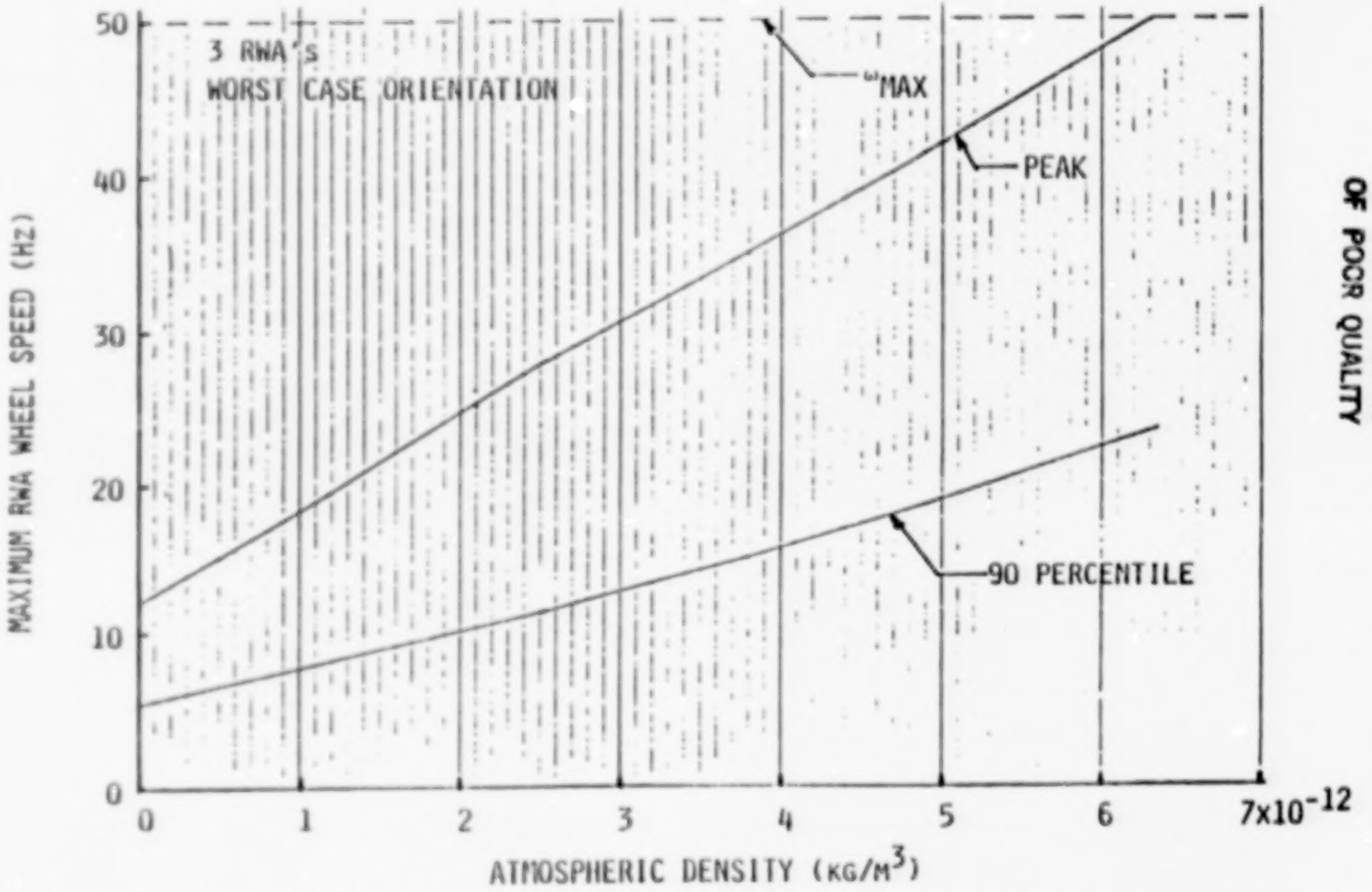
ST POINTING SYSTEM

MOMENIUM MANAGEMENT
RWA SPEEDS VS TIME



THE EFFECTS OF ATMOSPHERIC DENSITY ON THE ST PCS

MAXIMUM RWA SPEED VS
ATMOSPHERIC DENSITY



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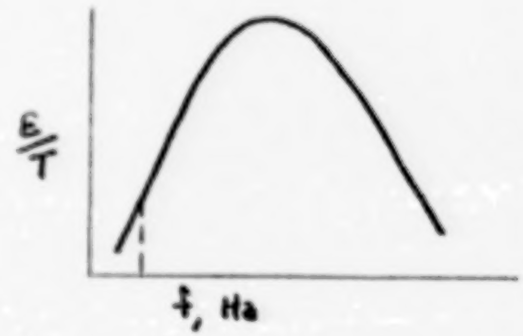
THE EFFECTS OF ATMOSPHERIC DENSITY ON THE ST PCS

MECHANISMS BY WHICH THE ATMOSPHERIC DENSITY EFFECTS THE PCS

AERODYNAMIC TORQUE $= \frac{1}{2} \rho V^2 A_{REF} (\underline{C} \times \underline{R} + \underline{C}_M)$

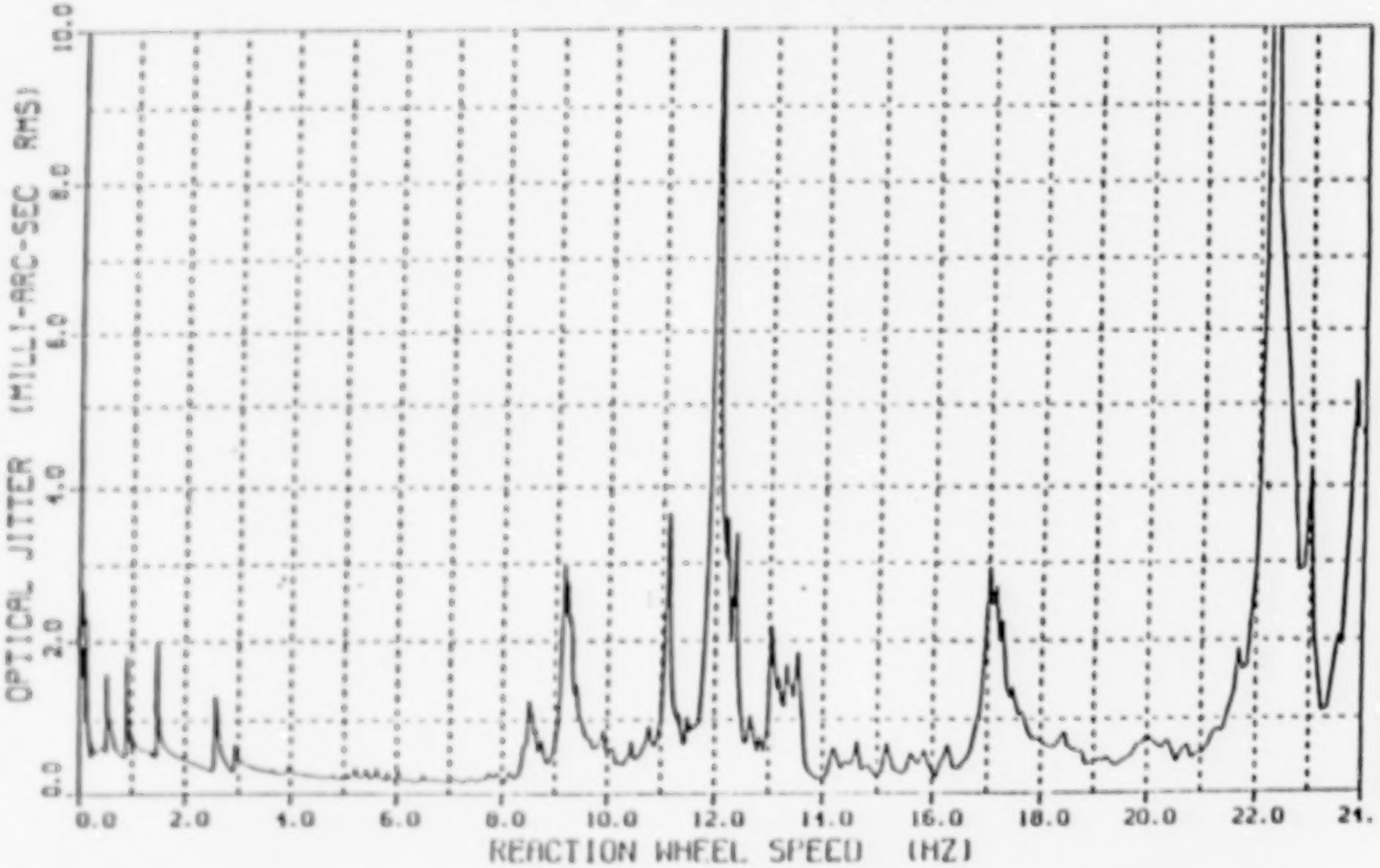
DIRECT POINTING ERROR SOURCE DUE TO T_A IS SMALL DUE TO THE INTEGRATOR IN THE CONTROLLER AND THE RELATIVELY LOW FREQUENCY OF T_A.



INDIRECT POINTING ERROR SOURCE DUE TO INCREASED REACTION WHEEL SPEEDS. AS THE WHEEL SPEEDS INCREASE DUE TO INCREASED T_A, THE FREQUENCY SPECTRUM AND AMPLITUDE OF VIBRATIONS FROM THE WHEELS INCREASES, INTERACTING WITH THE ST STRUCTURE TO DISTURB THE POINTING.

ANGULAR MOMENTUM BUDGET IS EFFECTED BY INCREASED T_A. AS THE MOMENTUM REQUIRED TO ACCOMMODATE DISTURBANCE TORQUES INCREASES, THE MOMENTUM AVAILABLE FOR MANEUVERING DECREASES, RESULTING IN A LESS AGILE SYSTEM.

R.W.A. 1003 INDUCED JITTER
AT THE WF/PC DETECTORS (.003 DAMPING)
DYNAMIC MODEL OF OCT. 1982



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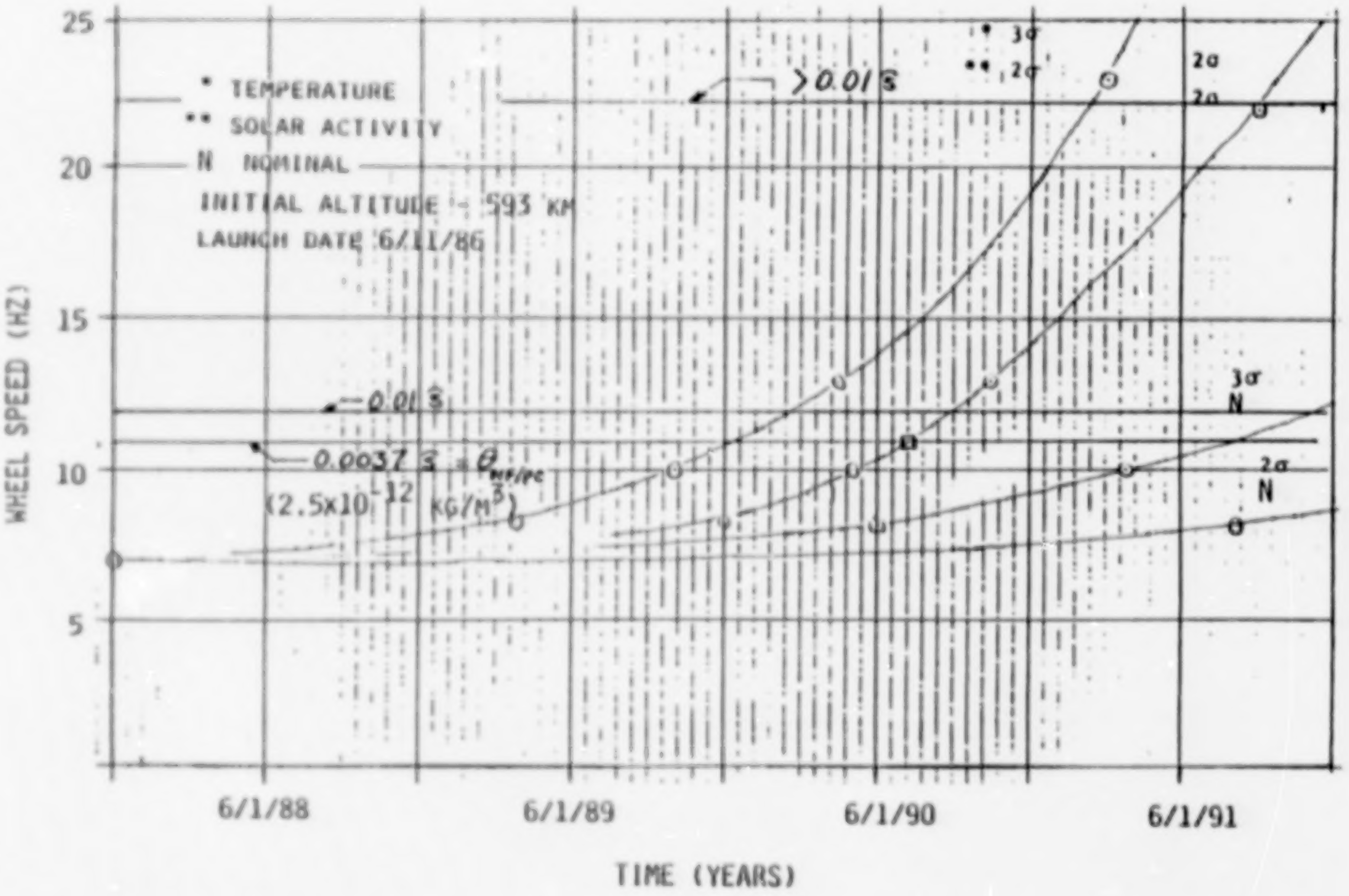
THE EFFECTS OF ATMOSPHERIC DENSITY ON THE ST PCS

WHEEL SPEED VS TIME



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EFFECTS ON ANGULAR MOMENTUM BUDGET

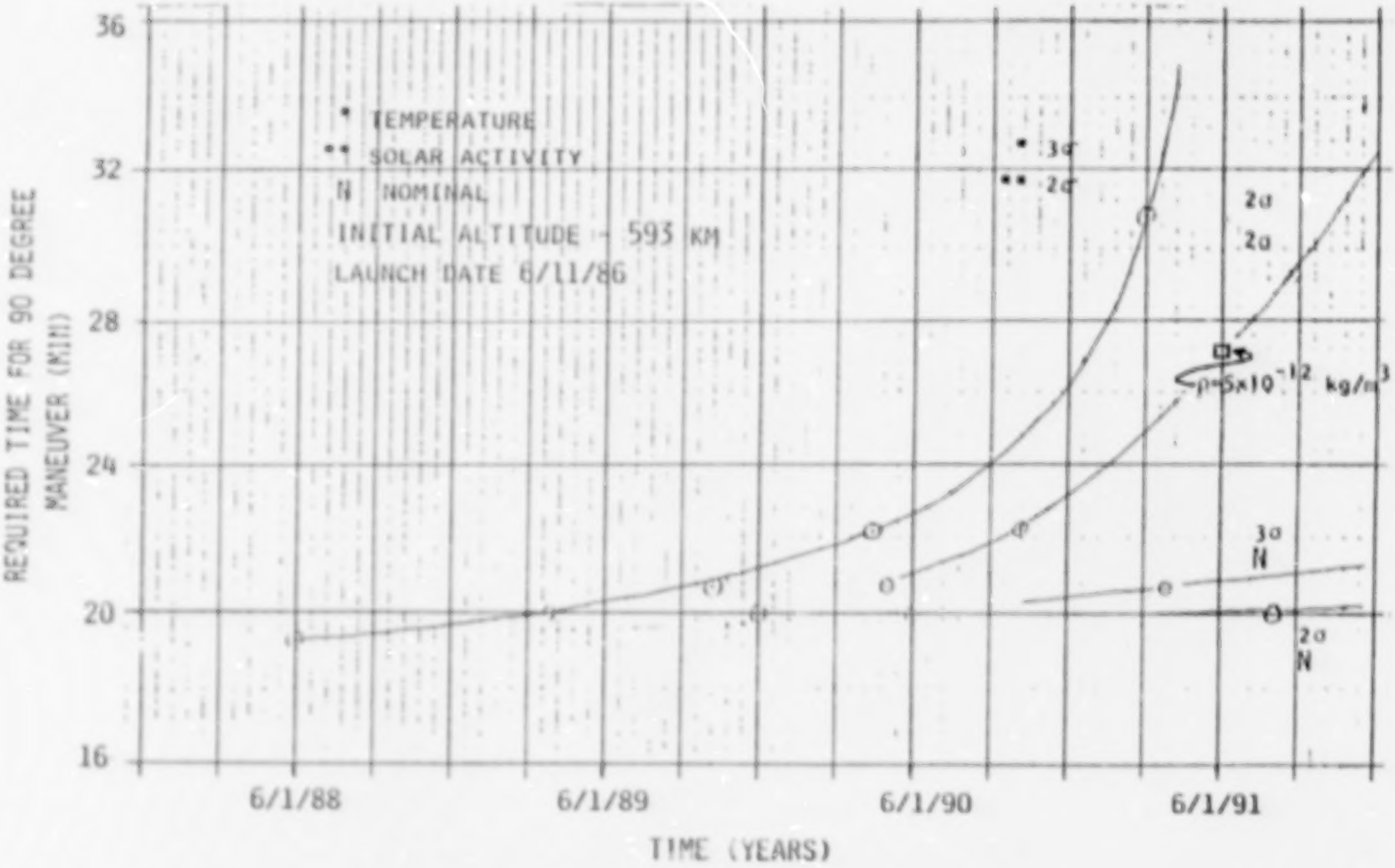
MOMENTUM ALLOCATIONS (NOMINAL)

	MOMENTUM, NM
GRAVITATIONAL TORQUE	50
AERODYNAMIC TORQUE	100
MANEUVERING	300
CONTROL SYSTEM AND OTHER	50
TOTAL	500

SINCE THE CAPACITY OF THE MOMENTUM STORAGE SYSTEM IS FIXED AT 500 NM, AN INCREASE IN ATMOSPHERIC DENSITY FROM ITS NOMINALLY ASSUMED VALUE WILL REQUIRE A REDISTRIBUTION OF MOMENTUM, REDUCING THAT ALLOTTED FOR MANEUVERING.

THE EFFECTS OF ATMOSPHERIC DENSITY ON THE ST PCS

TIME FOR 90 DEG MANEUVER VS TIME



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RECOMMENDATIONS FOR DENSITY MODELING

- THERE IS A NEED FOR A MODEL THAT ACCURATELY PORTRAYS SHORT TERM VARIATIONS.
- THERE IS A NEED FOR LESS COMPLEX MODELS THAT ARE APPLICABLE OVER LIMITED ALTITUDES, E.G., 400-700 KM.

PRECISION TRACKING/NAVIGATION - NAVY SATELLITES

M. Crawford, U.S. Navy

Precision satellite orbit requirements and tracking, such as for the Transit Program, are very density-sensitive. The Transit satellite is in a 600 n.mi. orbit, with a 30 m tracking accuracy requirement. The atmospheric density program used is a Jacchia program modified to make use of Transit tracking data. There are problems with automatic prediction of satellite position during geomagnetic storms due to the inadequate models, and there is manual intervention at such times.

In summary, the most pressing need is for more accurate and reliable short term forecasts of solar and geomagnetic storm activity.

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NORAD SATELLITE TRACKING

Joseph J.F. Liu, SPACECMD

NORAD routinely tracks about 6000 orbiting objects. During the last 30 days of orbital time, prior to re-entry, special perturbations are used in the orbital update procedure. Besides routine orbit determination, NORAD does special tasks such as predicting satellite orbit conjunctions within 20 km, ephimerides of weather satellites, satellite decay predictions and other studies. Since their mission is operational, they do not store the data from their analyses. The ballistic coefficient ($C_d A/m$) is not known for most of the orbiting objects. (In principle it could be derived by numerical fitting, assuming that it is constant for a particular density model, but this has not been done.) If a ballistic coefficient were derived that was consistent with one density model, it might give erroneous results if used with a different density model. Given the ballistic coefficient, density values could, in principle, be obtained from their tracking data. The densities would represent an integrated mean over the orbital path near perigee. They would be model dependent and would not necessarily represent the "real" density.

NORAD's experience is that the Jacchia 1964/1965 model is as good as more recent models for all levels of solar activity, and runs significantly faster, since it is less complex. However, if solar flux (as indicated by F10.7) and geomagnetic activity (Ap) are known, then the density model needs improvement. Their experience is that the specified model altitude limitation of 1000 km does not appear to restrict the utility of the earlier models for predictions of highly eccentric satellite orbits.

It might be that orbital tracking data could be made available for scientific use, although the model dependence and lack of knowledge of the ballistic coefficient would make interpretation difficult.

In summary, the primary need is for reliable forecasts of F10.7 and Ap in the 1 to 4 week time scale. Forecasts over longer time spans would also be useful for special projects.

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REPORT OF THE USAF SCIENTIFIC ADVISORY BOARD

AD HOC COMMITTEE ON AERONOMY

USFA SCIENTIFIC ADVISORY BOARD, HQ USAF (NR), WASHINGTON, DC

MAY 1977

SPECIFIC RECOMMENDATIONS AND SUGGESTIONS

TO IMPROVE THE EXISTING CAPABILITIES

- FORECASTING AND SPECIFICATION OF IONOSPHERIC PROPERTIES
- SOLAR PARTICLE RADIATION FORECASTING
- FORECASTING OF NEUTRAL DENSITY

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NORAD/SPACECMD DAILY CATALOG MAINTENANCE

- MAINTAIN AND UPDATE ABOUT 6,000 OBJECTS
- MORE THAN 3/4 OF THE OBJECTS ARE UNDER SIGNIFICANT DRAG EFFECTS

CURRENT NORAD PROJECTS USING EMPIRICAL ATMOSPHERIC DENSITY MODEL

- o TIP (DECAY PREDICTION)
- o DMSP/NOAA (WEATHER SATELLITE EPHEMERIS)
- o COMBO (ORBIT CONJUNCTIONS)
- o SENSOR CALIBRATIONS
- o SDI
- o OTHERS

DEFICIENCIES

- ACCURACY
- EFFICIENCY
- $F_{10,7}$ AND A_p PREDICTIONS
- ALTITUDE LIMITATIONS

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NORAD/SPACECMD COMMENTS CONCERNING THE ATMOSPHERIC DENSITY MODELS

Joseph J.F. Liu
Directorate of Astrodynamics, SPACECMD

1. Recent Models do not produce more accurate neutral densities (although they require more computer time), regardless of the level of solar activity. This implies that there has been no measurable improvement of the calculation of neutral density since the early 60s.

2. With known solar flux and Ap inputs, the density evaluation needs improvement.

3. For highly eccentric orbits which span low to high altitude, the accuracy generated by JNSSC which has an altitude limitation of 1000 Km remains comparable with those obtained by more recent models. This implies that either the density at 1000 Km and above is insignificant or that the values provided by the recent models at high altitudes may not be reliable or both.

4. Prediction accuracies obtained through the use of precision data from the defense mapping agency are generally comparable to those obtained by using operational sensor data. This implies that the prediction accuracy problem is not necessarily caused by less accurate observations.

5. The above findings remain the same whether we use a special perturbation theory or a simplified semi-analytic orbit theory.

6. Improved short and long term forecasts on solar activity and Ap are required to support current and future operations. One to four weeks predictions would be very helpful. Longer predictions are also needed for some special projects.

7. The definition of the mean solar flux F10.7 is not universal.

8. A unified model including low and high altitude densities is needed.

9. New models using new parameters should be investigated.

ORBITAL ATMOSPHERE PHYSICS AND DYNAMICS

Chairpersons: R. Roble, T. Killeen

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ORBITAL ATMOSPHERIC PHYSICS AND DYNAMICS

Raymond Roble, National Center for Atmospheric Research
Timothy Killeen, University of Michigan

There are two ways of modeling the upper atmosphere. One is the empirical model that makes use of experimental data on means and excursions from the mean and fits the data in a self-consistent manner. Although useful, such a model sweeps the physics under the rug, and will eventually reach a plateau beyond which progress can only be made by dealing with the underlying processes involved.

The other approach is to deal directly with the physical processes. This is difficult since what is happening is extremely complex. Data measured using an interferometer to give Doppler shifts of airglow lines showed 300-800 m/sec winds with a complex structure in the upper region of the thermosphere at high latitudes. Ionospheric electric fields, strongly influenced by interaction with the solar wind, drive the ionized component and large neutral winds result due to momentum transfer between the charged particles and the neutrals. Frictional heating results from movement of ions through the neutrals, which also influences the compositional structure. These are examples of the complex interactions involved.

Roble has adapted the NCAR General Circulation Model (tropospheric) for use at thermospheric altitudes - the Thermospheric General Circulation Model (TGCM). The model makes use partly of primitive equations and partly of empirical data for some quantities such as electron density, magnetic field, and ion drift.

Roble remarked that the Jacchia 1971 model appears to give more reliable composition while earlier models work better for density. An advantage of the earlier models was that they used Bates temperature models, which allowed for exact analytical integration. Later models introduced a more refined temperature profile fitting scheme which required numerical integration but failed to improve density calculations. It is surprising that the earlier Jacchia models work as well as they do for density, since compositions found by the OGO satellite are completely in variance with Jacchia model predictions. Future revisions of the Jacchia model are planned that will include "pseudotemperatures", a procedure where each component has its own effective temperature.

One might argue several ways regarding choice of models:

1) If there were little difference in density results between old models and new models, then it might be better to use the newer ones, since they yield better composition. Composition enters in through differing behavior of various

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components with altitude and season (viz. the observed large changes in helium seasonally and geographically), and through compositional influence on temperature structure. Composition also can influence the drag coefficient, and questions arise regarding activity of specific components such as surface erosion by atomic oxygen.

2) On the other side of the argument, there is the advantage of using density models that are consistent with past experience and that are "good enough" as well as being computationally efficient. Orbit data from NORAD and other sources are model dependent. Another important consideration is that once a model is specified, there is a considerable cost impact in making a change. Once contracts for a space program development have been finalized, any changes are difficult, costly, and undesirable from the standpoint of contract management.

Since new models will undoubtedly be introduced, due consideration should be given to the use of spherical harmonic expansions. There are definite advantages to using spherical harmonics: sizes of coefficients drop off quickly after the first few, so consistent models of various degrees of detail can be readily developed and new effects added with a minimum of disruption.

Roble showed the Workshop an impressive computer-generated animation of thermospheric motions.

ORBITAL ATMOSPHERE MODELING

Chairperson: G. Carignan

ORBITAL ATMOSPHERE MODELING
REMARKS AND DISCUSSION

George Carignan, University of Michigan

Present models are better at hindcasting than forecasting. When Kp values are known, the models are able to reproduce atmospheric density to around 15 percent. Much of the remaining error probably arises because the models fail to deal with small scale structures or dynamic processes which often are coupled to small scale structures. In order to achieve improvement, we should devise means for handling small scale structures and couplings. For forecasts, it is necessary to be able to predict solar and geomagnetic activity - to reliably forecast Kp or aa and F10.7. At present the likelihood of being able to accomplish this over long time intervals appears dim. More success is likely over short times intervals.

Standardization of the models employed by the user community should be considered. Competition among modelers is wholesome, but there should not be excessive duplication of effort. Another problem that has often been encountered is that user groups sometimes unknowingly use outmoded versions of a particular model, or even versions containing programming or data errors where corrected and updated versions exist. There would be much to be gained by using a model form that is readily updated. A central clearinghouse is also strongly suggested. This is a reason for considering the spherical harmonic formulation. Standardization and a centralized clearinghouse for model information appear to be constructive ideas, but in order to carry them out the Government would need to have a commitment to them. Somebody would need to assume central responsibility, and they would have to be adequately funded.

Another point is that the vast potential data base of NORAD tracking information is currently not being used for model improvement or verification. This bears looking into. But a problem [Smith] is that the NORAD information always has density coupled to C_dA/m. Decoupling would have to be done either through a sophisticated fitting procedure, or by restricting the analysis to those cases where C_dA/m is known. Another consideration is that experience shows that results obtained using a different model from the one that was used for the orbital data reduction can lead to spurious results.

[Gary Swenson, Lockheed]

Drag is difficult to predict for a complex body such as Skylab, with its solar panels, etc. Appendages such as solar panels can give lifting forces, influencing the overall body drag. The drag coefficient itself is influenced by such factors as constituent and surface chemistry, temperature, and material conditioning. Drag coefficient depends upon the velocity

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C-2

distribution of exiting particles. Glow studies bear on this - it is a complex interaction between chemistry and radiation. One conclusion is that in order to predict the effects of chemistry on the drag coefficient it would be necessary for a model to predict the density of individual constituents such as atomic nitrogen and atomic oxygen.

[Carignan] Users need to be more specific on their needs. For example, for an orbiting satellite, is information needed on the order of minutes or on the order of orbits? [Smith] It appears that for some applications the present models, and even some from the past, are adequate. For other applications they are not.

Perhaps it would be possible to design a standardized model that would allow for updating and improvement, and would have various hierarchies of complexity depending upon the application. Use of spherical harmonics would help in providing a means for adding greater scale detail.

Note that from the standpoint of the NASA program manager, it is essential to stick with the original criteria specified to the contractors. To change criteria in midstream would be very expensive. As an example, criteria for the space station are being specified right now. They will be firm by next year.

[Carignan] And they are apparently still using 1970 models...

[Smith] For drag that is probably quite all right. For composition it would not be. Composition is of less importance to the Space Station except for the matter of atomic oxygen and its effects on surface erosion. However, as Swenson pointed out, perhaps the other minor constituents are playing a more important role than we had thought.

[Slowey] Judging from experience, for drag studies you probably should use models that are derived from drag data.

[Smith] An important question is this: Do the users want predictions or do they want statistics? It would appear that although they naturally would like reliable predictions, that is impossible to achieve over time scales longer than a few days or weeks, and even for those time periods the predictions are of questionable reliability. However, we should be able to provide statistics, at least in some cases. That would mean, for example, that the engineers would be able to plan for adequate momentum management - to desaturate reaction wheels over the lifetime of a particular system such as the space station.

UPPER ATMOSPHERE

SUMMARY AND POSSIBLE RECOMMENDATIONS

G. Carignan

The Workshop heard presentations from thermospheric modelers and from experimentalists who have compared the models to measurements. These presentations were augmented by extended discussion by users, scientists and other interested participants. The results of these deliberations can be summarized by identifying several important issues and associated possible recommendations.

ISSUE I: The models being commonly used are able to reproduce the actual atmospheric density with a standard deviation of approximately +15% after the actual Ap and F10.7 are known. It is believed that a significant part of the discrepancy comes from failure of the models to represent small scale (~ 5 degrees in latitude and longitude) structures.

RECOMMENDATION: Models should be upgraded to enable better representation of variations at smaller scale than they currently do. It is recognized that some variations, e.g. individual gravity waves, cannot be modeled. The cusp is an example of a feature that can and should be better modeled.

ISSUE 2: Few, if any, of the currently used models treat dynamical processes (winds). This defect is of particular importance at high latitudes.

RECOMMENDATION: Attempt to integrate the wind field representations of the numerical models into the user models in an efficient and least cumbersome way.

ISSUE 3: The ability to predict atmospheric density is inextricably dependent on ability to predict F10.7 and geomagnetic indices.

RECOMMENDATION: a) Quantify the uncertainty in predictability of these quantities as a function of prediction interval.

b) Support research aimed at improving predictability of solar variability.

ISSUE 4: Model users generate information that can be valuable feedback to the modeling process. The implementation of this obviously beneficial activity is not trivial, but if done well, could be cost effective.

RECOMMENDATION: Feedback from model users to modelers should be encouraged and supported.

ISSUE 5: The measurements required to support a continued viable program in predicting the state of the thermosphere are not being routinely made. It is important to monitor several atmospheric variables to provide continuity to the data base that has enabled the progress to date, to track the long term variability and to improve understanding and prediction capability.

RECOMMENDATION: Plan and support a thermosphere "weather" satellite or payload for the shuttle and space station.

ISSUE 6: Competition amongst various workers modeling the thermosphere is wholesome, but there does appear to be some unnecessary and perhaps undesirable duplication of effort by both modelers and users.

RECOMMENDATION: The desirability of standardizing the atmospheric model and centralizing the management of the modeling and associated research should be carefully evaluated.

SUMMARY OF ISSUES

A. Hedin

1. While prediction of drag force appears to have not advanced much in the last decade, the description of composition and temperature variations has advanced considerably.

2. How many different models for different purposes should be provided? Composition is very much an engineering concern for surface degradation and glow problems. It also has some influence on drag and inaccurate drag coefficients may be degrading the calculation of drag force using more accurate atmospheric composition models.

3. Are we failing to allow for the evolution of engineering concerns and providing misleading answers by continuing to promote a 15 year old model to be used for the next decade. J70 is rarely referred to or compared to other data in the current scientific literature.

4. How are we to keep the models current or improving with the lack of current measurement missions and lack of appropriate drag analysis for objects currently in orbit.

5. What time scales of variability are important for engineering problems? The models may be better for some purposes than comparisons with high time resolution data suggest.

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LIMITATIONS TO MODELING THE THERMOSPHERE AND EXOSPHERE

John Slowey, Smithsonian Astrophysical Observatory

Correlations have been noted between solar 10cm radio flux, the indices of geomagnetic activity, and what happens in the atmosphere. There are also correlations between events in the troposphere and density in the thermosphere. Gravity waves in the thermosphere are not handled in existing models. A reasonable estimate is that they contribute perhaps ten percent to the deviation between model density values and the effective density as it influences satellite orbital motion. Another factor is atmospheric composition which influences density through the different scale heights of components of different molecular weight in this regime.

[Carignan] We should note that there are more gravity waves at high latitudes and also more at high Kp. This may account for the observed deviations.

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EMPIRICAL MODELING OF THE THERMOSPHERE: AN OVERVIEW

A. Hedin, NASA/Goddard Space Flight Center

Hedin gave a summary of thermospheric density modeling history and standard atmospheres. In particular, he compared and contrasted the approaches of the Jacchia and MSIS models. His conclusions were that the Jacchia models are best if drag is the primary concern. MSIS is superior for variations in composition and temperature variations and comparison with theoretical models is facilitated by the use of spherical harmonics, which also provide a simple and consistent way of obtaining simplifications.

ADVANTAGES/DISADVANTAGES

1. Jacchia

    a. Theoretically best if drag is primary quantity desired without high resolution and for satellite geometries and orbits similar to those used in generating the model. However, drag coefficients used in density derivation need to be more carefully specified if original drag is to be reproduced. Inaccurate specification of composition (e.g. He bulge) may result in inaccurate drag.

    b. Absolute total density dependent on the drag coefficient rather than the instrument calibration. However, dependence of drag coefficients on composition and extreme geometries may be a problem. Model predictions of composition and temperature are derived from auxiliary data or assumptions and may not be realistic.

    c. Formulation has particular difficulty coping with minor constituent variations found by mass spectrometers and cumbersome pseudotemperatures of J77 help only a little.

2. MSIS

    a. Best for composition/temperature variations, but agrees with drag models in overall averages.

    b. Provides better resolution of variations (including total density) in local time, etc.

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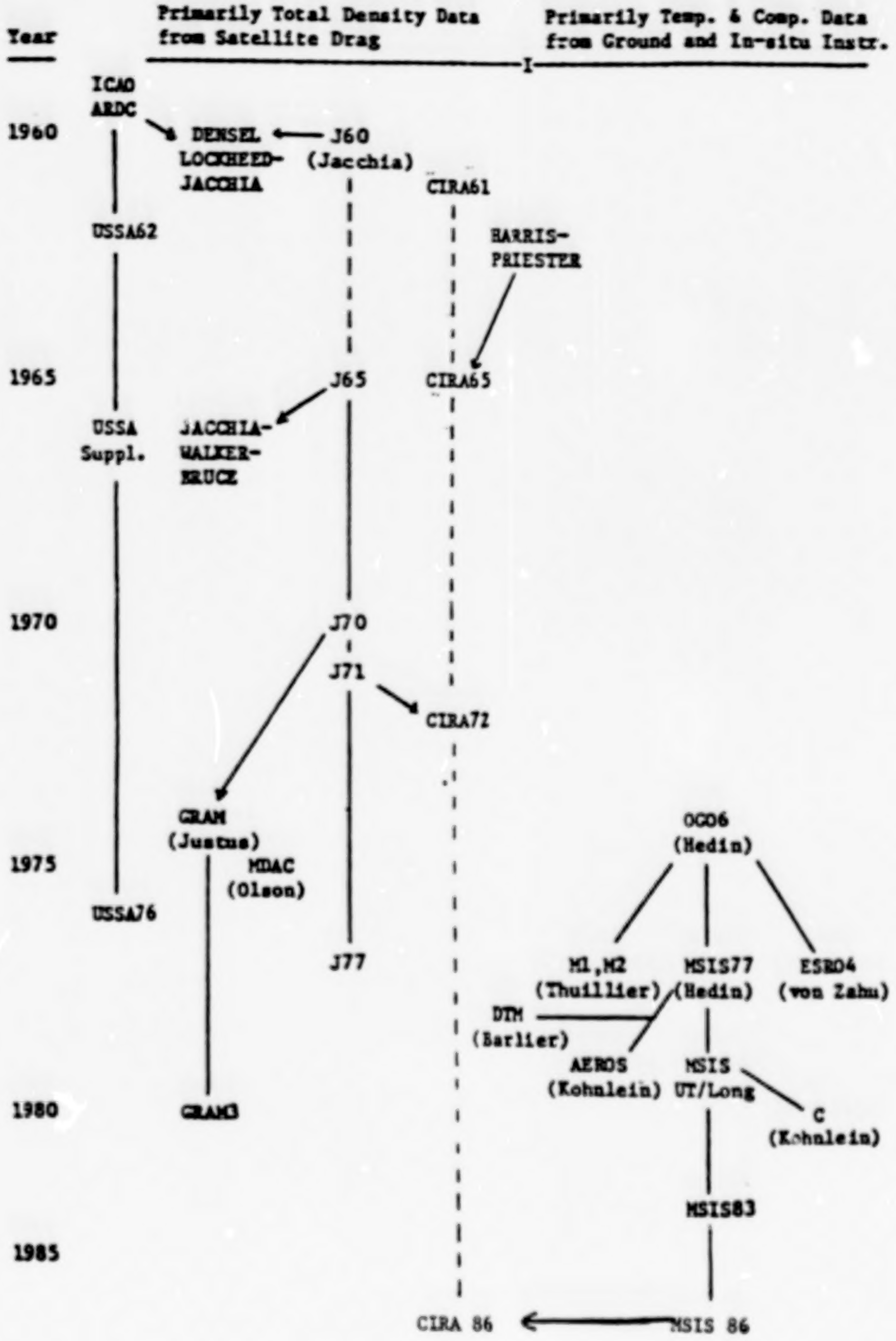
c. Absolute densities dependent on individual calibration constants for contributing instruments but model accuracy should be better than that of an individual instrument.

d. Spherical harmonics facilitate systematic increase in model resolution and comparison with theoretical models. Similarly, complexity can be reduced if desired by dropping higher harmonics or unneeded effects.

e. No numerical integration for faster execution speed.

Historical Development of Empirical Thermosphere Models


Year
Primarily Total Density Data from Satellite Drag
Primarily Temp. & Comp. Data from Ground and In-situ Instr.
ICAO
ARDC
1960
DENSEL
LOCKHEED-
JACCHIA
J60
(Jacchia)
CIRA61
USSA62
HARRIS-
PRIESTER
1965
J65
CIRA65
USSA
Suppl.
JACCHIA-
WALKER-
BRUCE
1970
J70
J71
CIRA72
GRAM
(Justus)
OGO6
(Hedin)
1975
MDAC
(Olson)
USSA76
J77
M1,M2
(Thuillier)
MSIS77
(Hedin)
ESRO4
(von Zahn)
DTM
(Barlier)
AEROS
(Kohnlein)
MSIS
UT/Long
1980
GRAM3
C
(Kohnlein)
MSIS83
1985
CIRA 86
MSIS 86

MODEL DEVELOPMENT

A. Jacchia
  1. J65
    a. Earliest comprehensive model based on drag. Lower boundary at 120 km.
    b. Static height profiles as function of exospheric temperature assuming hydrostatic/diffusive equilibrium.
    c. First to include four principal effects (diurnal/seasonal, semiannual, solar activity, magnetic activity) using ad hoc formulas for exospheric temperature to fill gaps.
    d. Introduced Bates type temperature profile (which can be integrated explicitly).
  2. J70 & J71
    a. Lower boundary at 90 km and more complicated temperature profile requiring numerical integration.
    b. Refinements and expansions of ad hoc formulas.
    c. Included factor of three winter helium bulge.
    d. J71 raised atomic oxygen at 150 km over J70.
  3. J77
    a. Inclusion of some results from mass spectrometers.
    b. Magnetic coordinates for magnetic activity effects.
    c. Composition phase through pseudo-temperatures.

B. OGO-6/MSIS
  1. OGO-6 (1974)
    a. Earliest comprehensive model based on mass spectrometer data.
    b. Bates temperature profile above 120 km.
    c. Spherical harmonics for geographical/local time coordinates.
    d. Variable boundary at 120 km for He and O to represent phase differences between constituents. Height profiles assuming hydrostatic/diffusive equilibrium.
    e. Temperature inferred from N2 agreed well with incoherent scatter.
  2. MSIS 77
    a. Same format as OGO-6.
    b. Used mass spectrometer density data from five satellites and temperatures from four incoherent scatter stations.
    c. Variable boundary also for N2 so temperature depends on incoherent scatter and N2 scale heights.
  3. MSIS 79
    a. Introduced UT/Longitude variations for quiet and magnetic active times (alternative to magnetic coordinates). Temperature maximum and He minimum near magnetic pole.
  4. MSIS 83
    a. Density and temperature data from mass spectrometers on seven satellites, from five IS stations, and from rockets.
    b. Extended profiles below 120 km to 85 km using analytically integrable temperature profiles.
    c. Includes major variations in temperature and density below 120 km.
    d. Improved resolution in prediction of magnetic activity variations using time history of 3hr indicies.

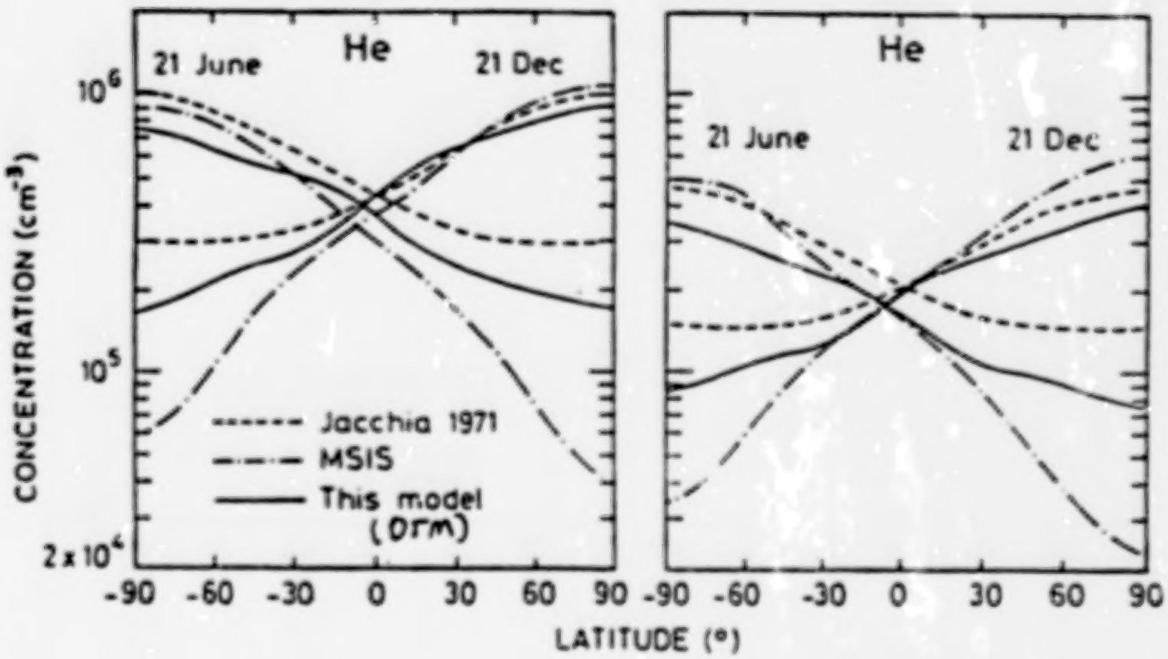


Fig. 13

Latitudinal variation of $n(He)$ at 1 000 km altitude. The left part corresponds to $F = \bar{F} = 150 \times 10^{-22}$ W m^{-2} Hz^{-1} and $K_p = 2$. The right part corresponds to $F = \bar{F} = 92 \times 10^{-22}$ W m^{-2} Hz^{-1} and $K_p = 2$. Comparison with Jacchia 1971 and MSIS models. Barlier (1979)

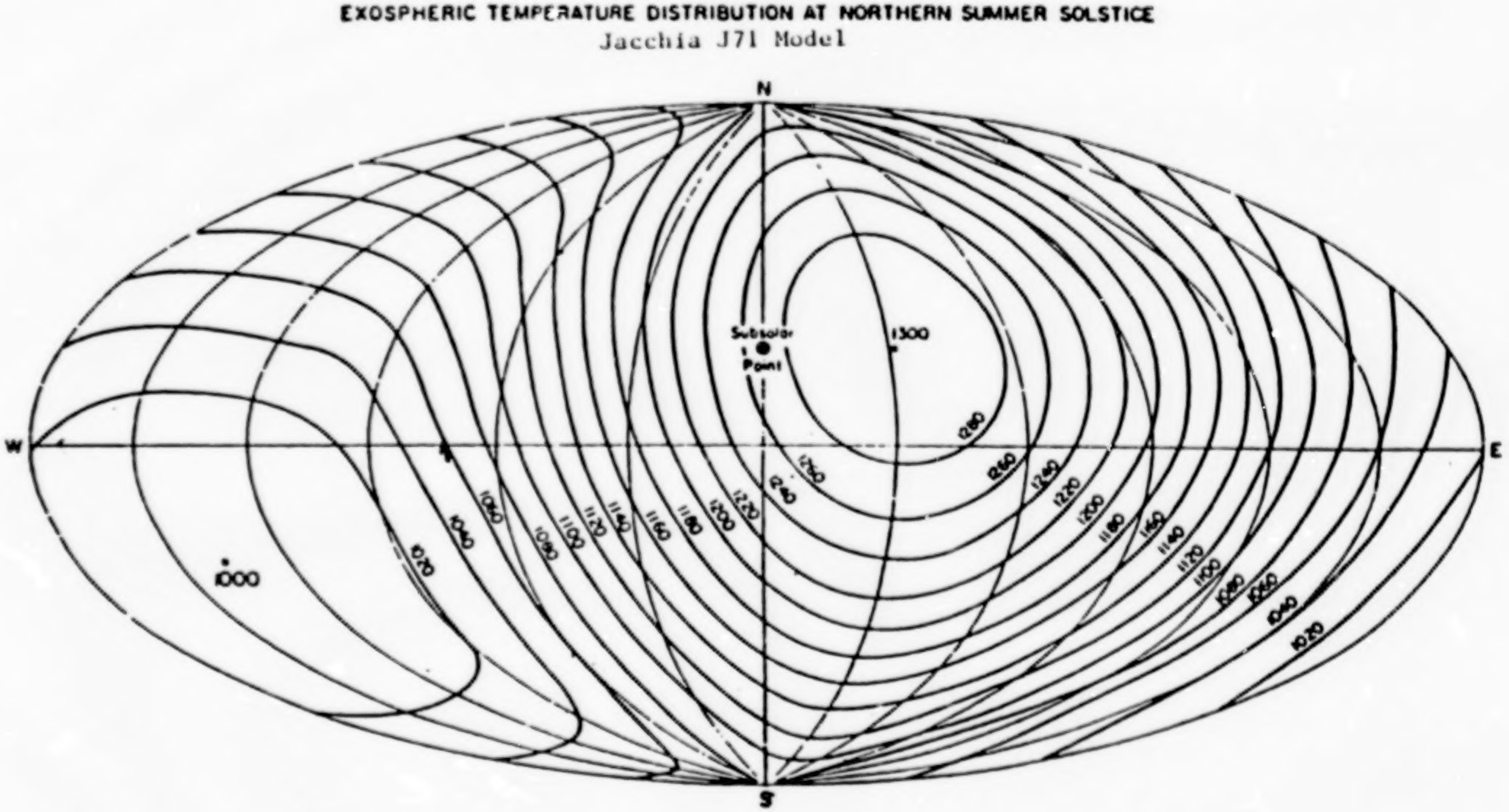

EXOSPHERIC TEMPERATURE DISTRIBUTION AT NORTHERN SUMMER SOLSTICE
Jacchia J71 Model
N
W
E
S
Subsolar Point
1300
1280
1260
1240
1220
1200
1180
1160
1140
1120
1100
1080
1060
1040
1020
1000

Figure 8. Exospheric isotherms (°K) above the globe, computed from equations (15) and (16), for the case when the minimum temperature is 1000°K. Aitoff's equal-area projection; meridians of local solar time and parallels of latitude are drawn 30° apart. Top, equinoxe bottom, northern summer solstice.

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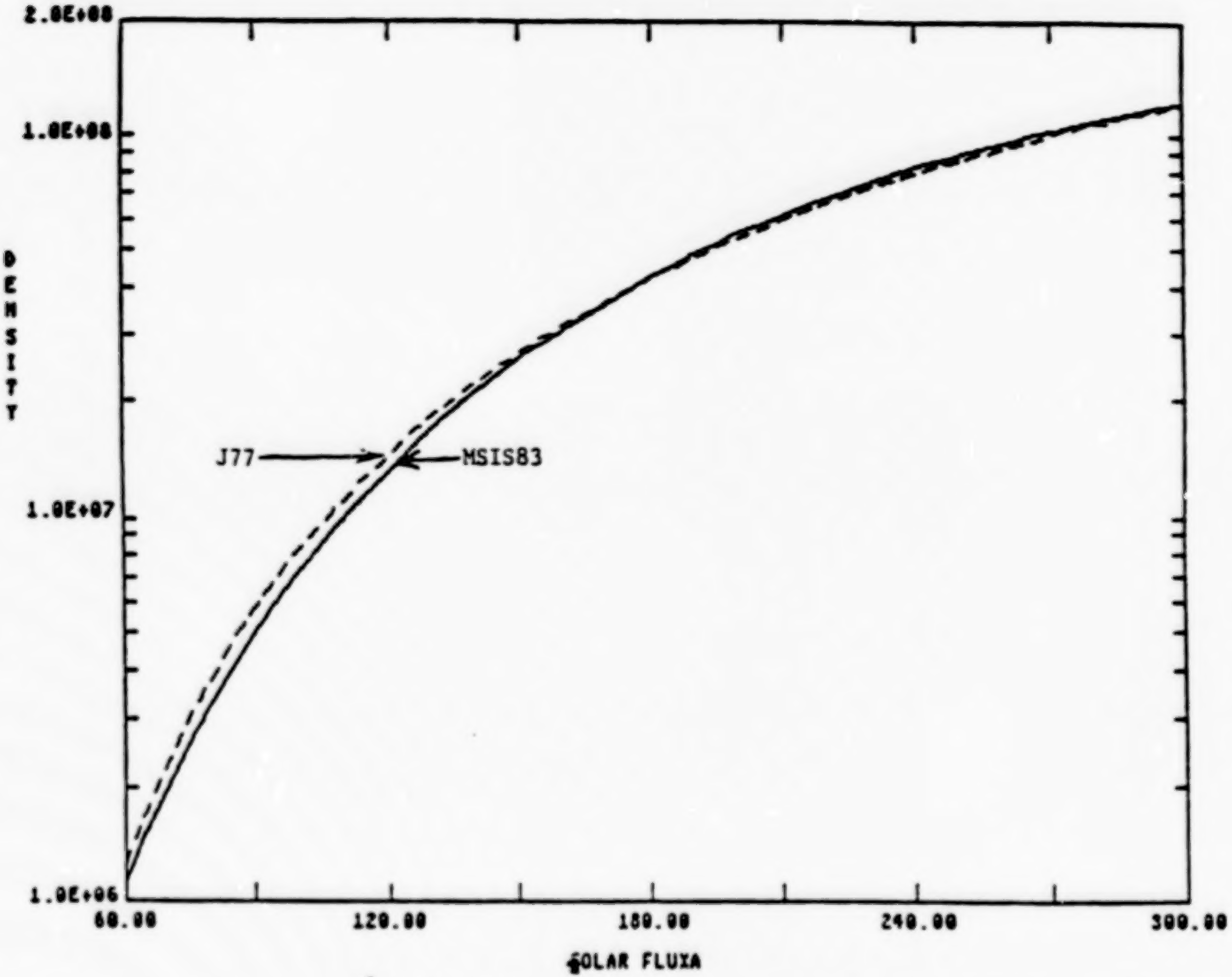

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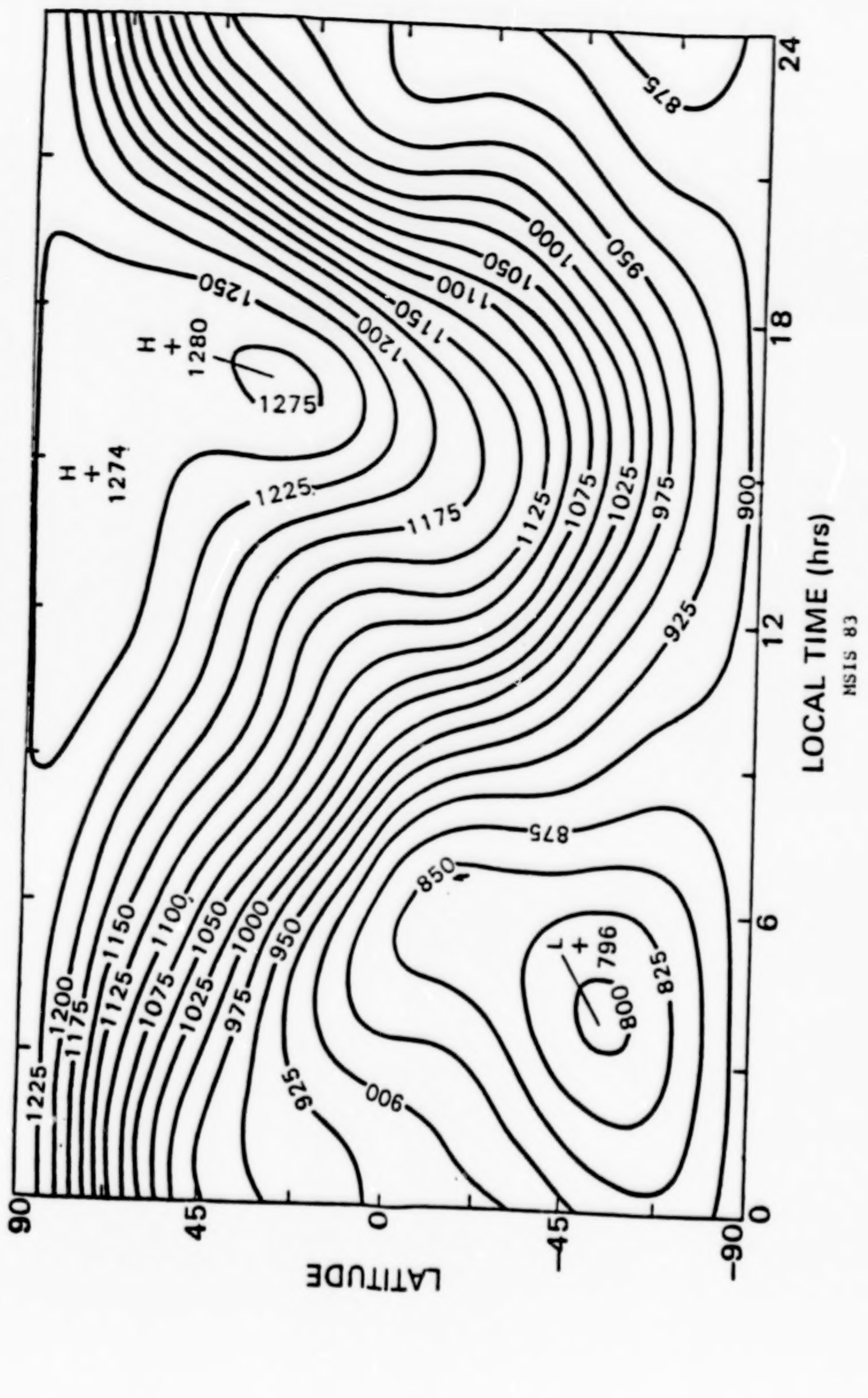

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-45
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18
24
MSIS 83
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+
1280
1275
1250
1225
1200
1175
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925
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825
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796

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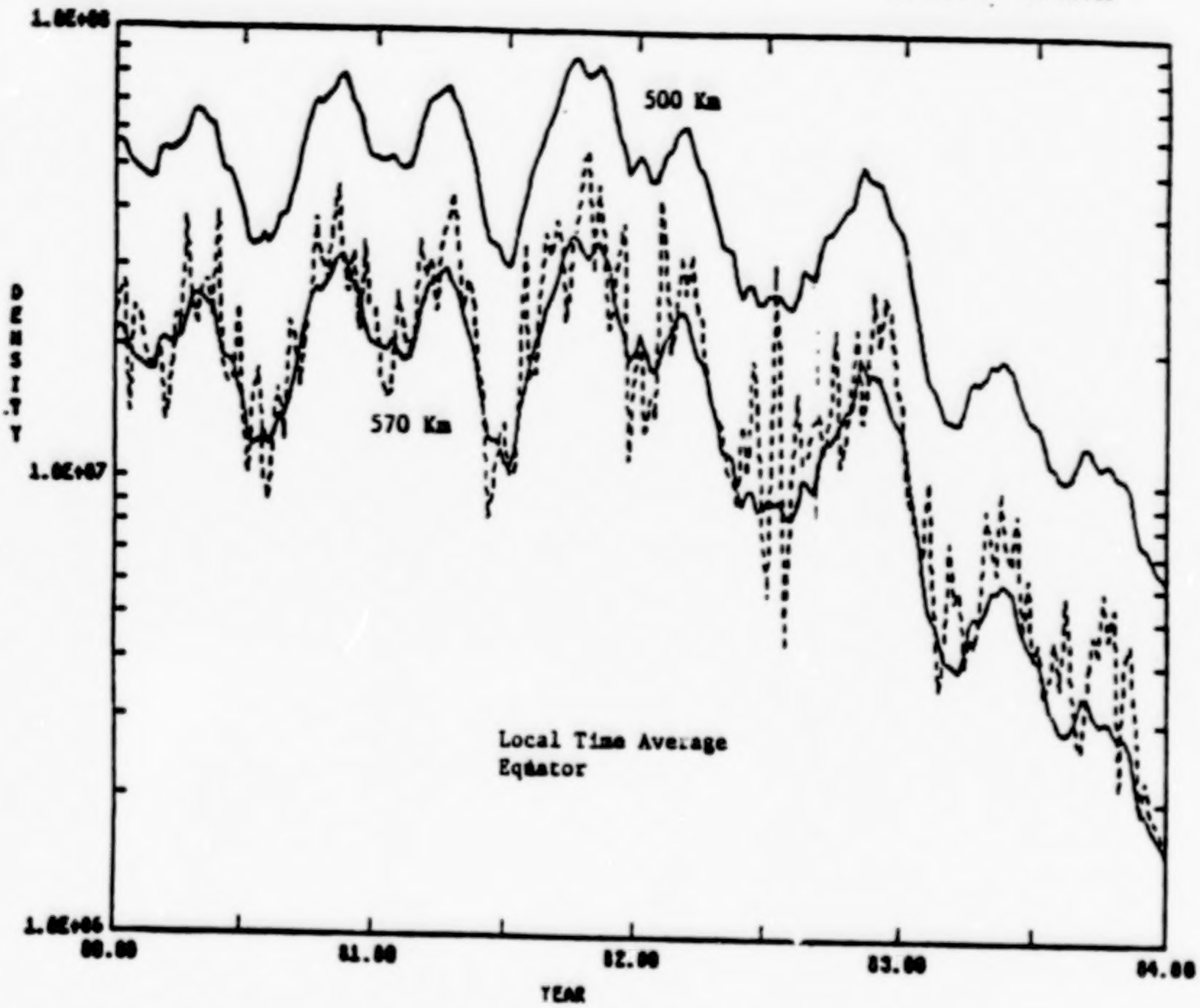

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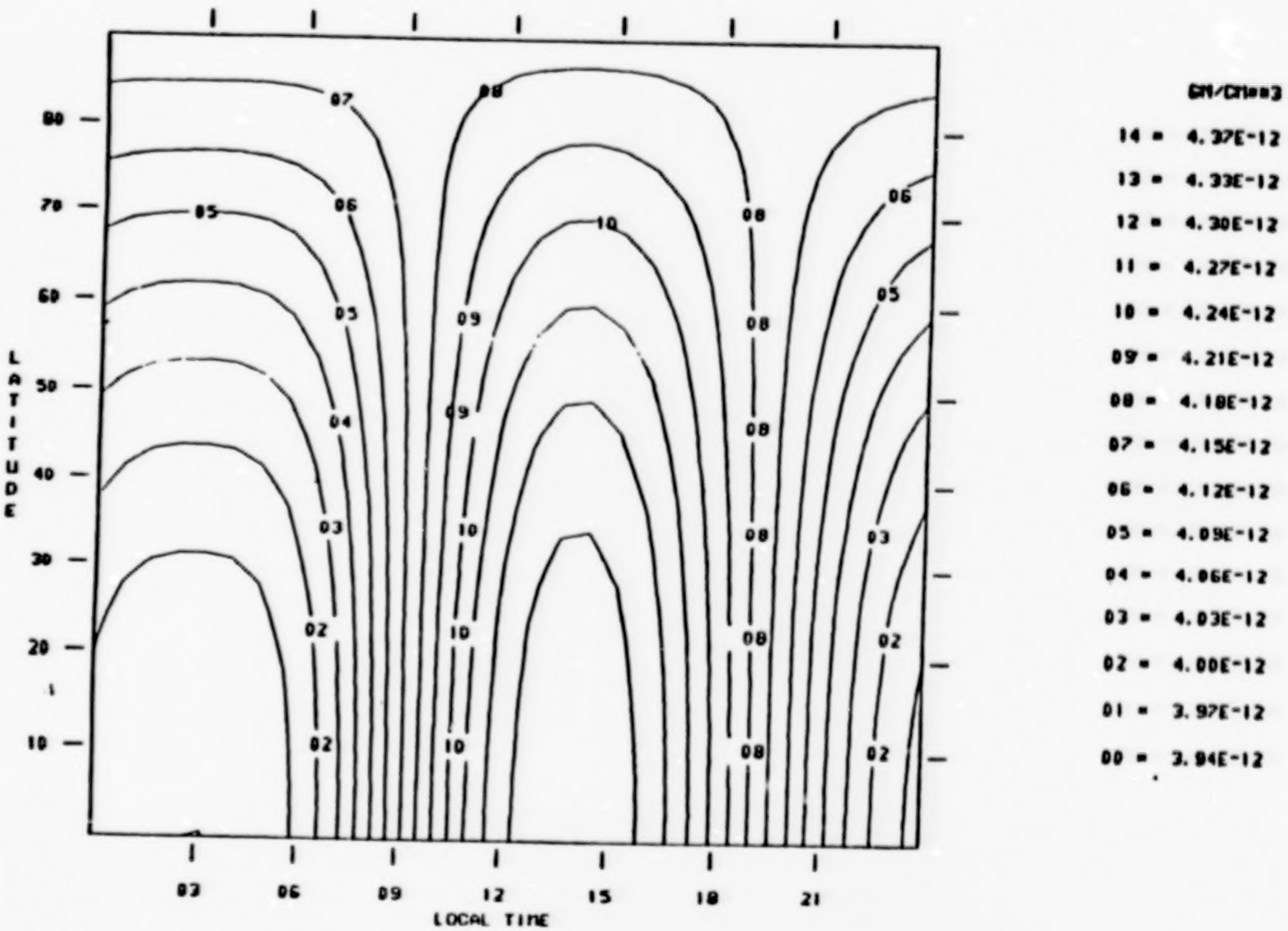
Table 4a. Density Ratio to MSIS-83 for N_2, O, and He.

		N_2			O			He		
Data Set	altitude	avg	sd	pts	avg	sd	pts	avg	sd	pts
OGO-6 (MS)	400-700	1.08	.27	659	1.15	.16	1276	1.18	.19	902
San Marco-3 (MS)	190-250	1.10	.20	77	.86	.15	24	1.09	.17	41
Aeros-A NATE (MS)	200-500	1.13	.47	321	1.14	.33	478	1.18	.42	466
AE-C NATE (MS)	190-400	1.13	.33	640	.91	.18	866	.68	.18	855
AE-C OSS (MS)	135-160+	.97	.15	440						
AE-C OSS (MS)	190-400	1.02	.26	319	1.08	.18	387	1.03	.23	371
AE-D OSS (MS)	140-160+	.99	.16	184						
AE-D OSS (MS)	190-400	.87	.33	99	1.01	.18	107	.78	.22	107
AE-E NACE (MS)	140-160+	1.01	.13	815						
AE-E NACE (MS)	190-450	1.00	.22	701	.87	.18	1019	.93	.17	1002
ESRO-4 (MS)	200-350	.88	.33	427	.83	.24	587	.84	.30	518
Rockets (MS)	100-120	.83	.36	35						
Rockets (MS)	110-160	.92	.30	28						
Rockets (MS)	190-300	.90	.32	39						
Arecibo (IS)	100-120	.92	.32	228						
Arecibo (IS)	110-135	1.14	.51	109						

MODEL = JACCHIA 71   F10.7 = 125.   ALT = 140. KM   KP = 2.   EQUINOX



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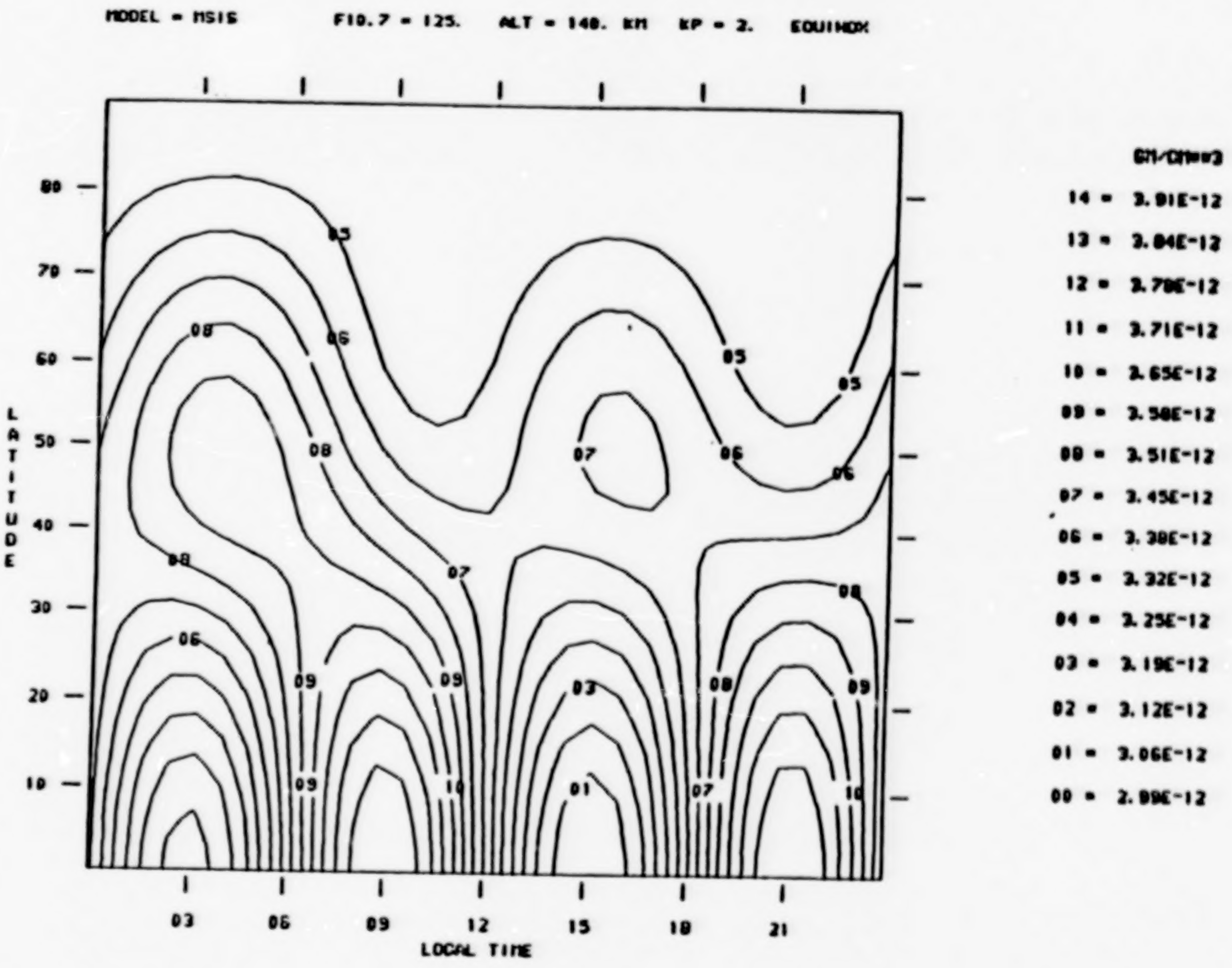
MODEL = MSIS
F10.7 = 125.
ALT = 140. KM
KP = 2.
EQUINOX
LATITUDE
80
70
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10
LOCAL TIME
03
06
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18
21
05
06
07
08
09
10
03
01
GM/CM**3
14 = 3.91E-12
13 = 3.84E-12
12 = 3.78E-12
11 = 3.71E-12
10 = 3.65E-12
09 = 3.58E-12
08 = 3.51E-12
07 = 3.45E-12
06 = 3.38E-12
05 = 3.32E-12
04 = 3.25E-12
03 = 3.19E-12
02 = 3.12E-12
01 = 3.06E-12
00 = 2.99E-12

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REQUIREMENTS FOR IMPROVED MODELING OF THE ORBITAL ATMOSPHERE

Frank A. Marcos, Air Force Geophysics Laboratory

Satellite accelerometer data are available for seven time periods during the period 1974-present. All seasons and latitudes up to 83° are covered. Deviations between the accelerometer data and current models are greatest for high geographic latitudes and high geomagnetic index, although about a 15 percent standard deviation persists between the models and the accelerometer data even at low latitudes and geomagnetically quiet times.

Accelerometer data give density times the ballistic coefficient, (C_dA/m), and it is therefore necessary to estimate the time-line of the ballistic coefficient in order to obtain density.

REQUIREMENTS FOR IMPROVED THERMOSPHERIC NEUTRAL DENSITY MODELS

FRANK A. MARCOS

AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MA

WORKSHOP ON UPPER AND MIDDLE
ATMOSPHERIC DENSITY MODELING

HUNTSVILLE, ALABAMA

19 NOV 85

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OUTLINE

- INTRODUCTION
- AFGL SATELLITE ACCELEROMETER DATA BASE
- RESULTS
    - MODEL EVALUATIONS
    - GEOMAGNETIC STORM ANALYSES
- DISCUSSION/CONCLUSIONS

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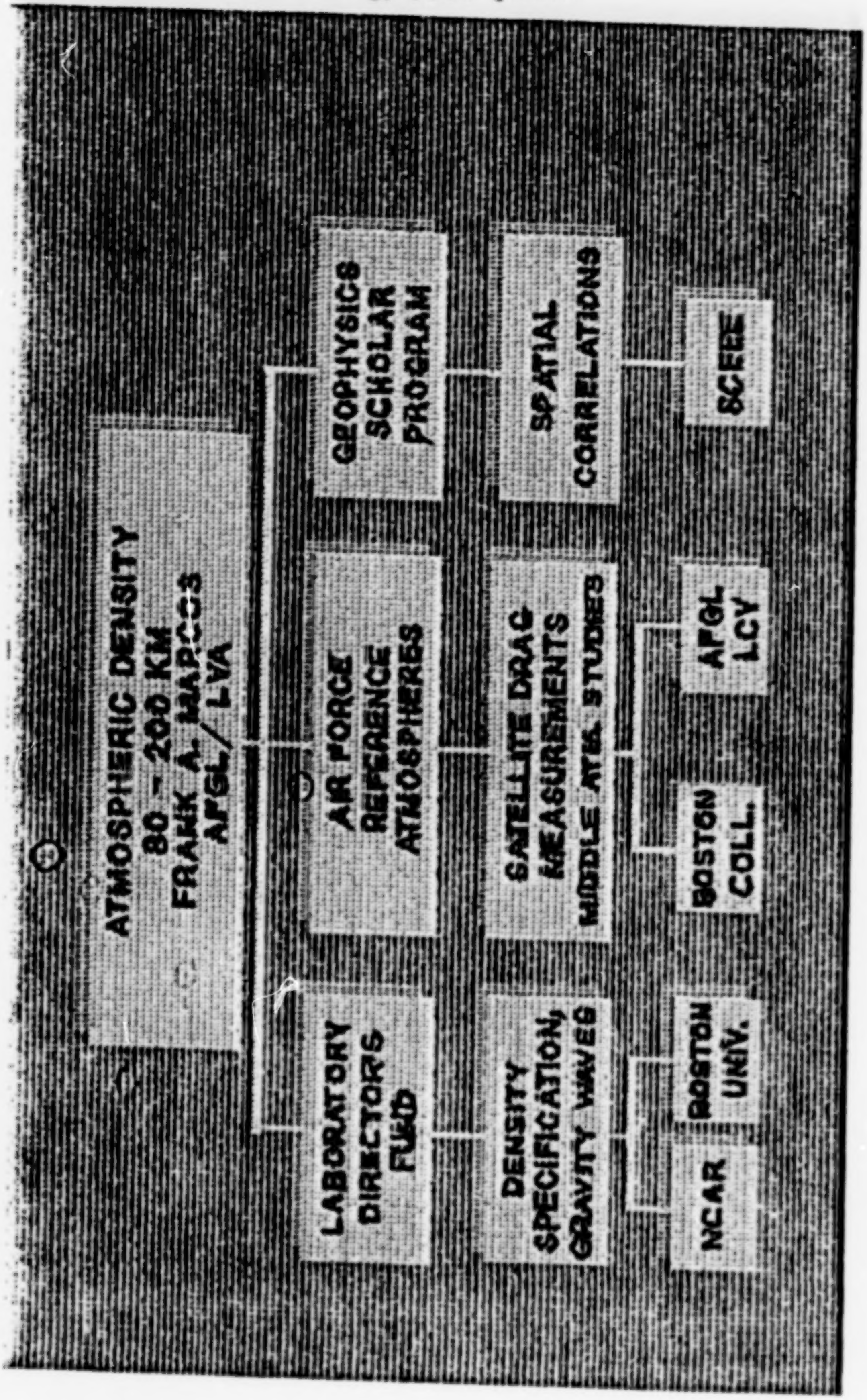

ATMOSPHERIC DENSITY
80 - 200 KM
FRANK A. MARCOS
AFGL/LVA

LABORATORY DIRECTOR'S FUND

AIR FORCE REFERENCE ATMOSPHERES

GEOPHYSICS SCHOLAR PROGRAM

DENSITY SPECIFICATION, GRAVITY WAVES

SATELLITE DRAG MEASUREMENTS
MIDDLE ATM. STUDIES

SPATIAL CORRELATIONS

NCAR

BOSTON UNIV.

BOSTON COLL.

AFGL LCY

SCEEE

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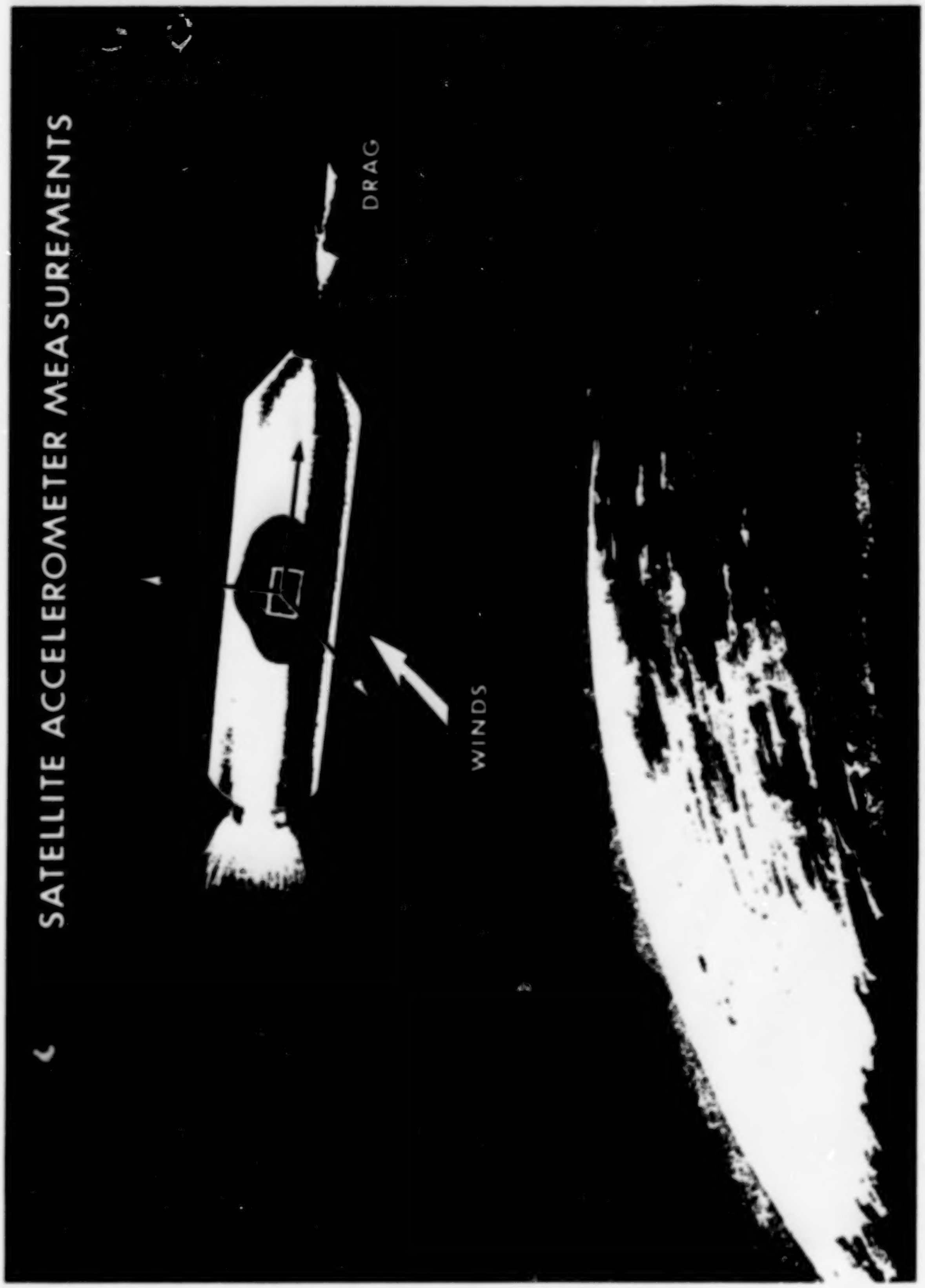
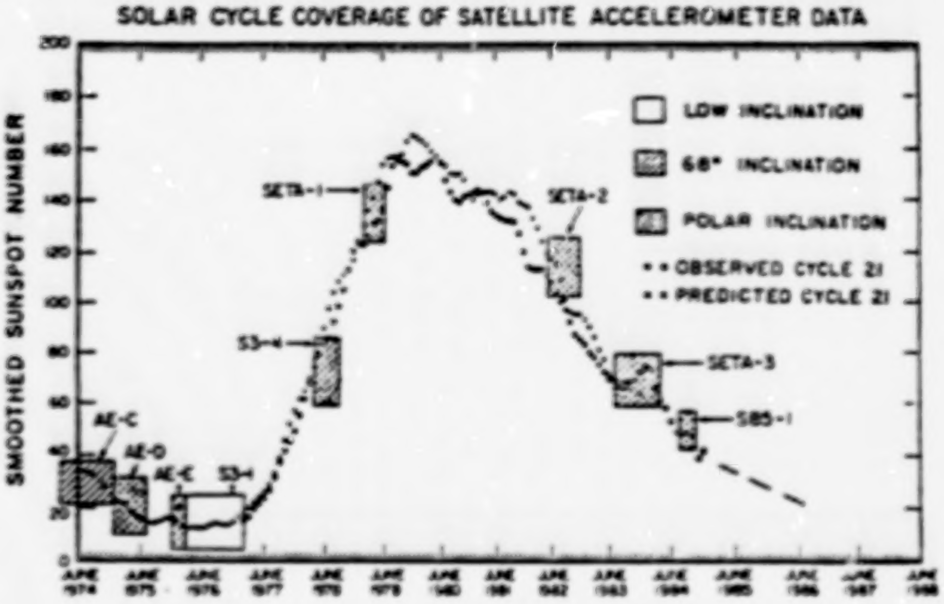

SATELLITE ACCELEROMETER MEASUREMENTS
DRAG
WINDS

Cartoon showing orientation of accelerometer axes with respect to aerodynamic drag and cross-track wind vectors.



Satellite accelerometer flight history and solar activity vs. time.

TABLE 1. SATELLITE ACCELEROMETER DATA SOURCES

Satellite	Data Acquisition Period
AE-C	Jan - Dec 74
S3-1	Oct 74 - May 75
AE-D	Oct 75 - Jan 76
AE-E	Nov 75 - Nov 76
S3-4	May - Aug 78
SETA-1	Mar - Apr 79
SETA-2	May - Nov 82

SATELLITE ACCELEROMETER DATA COVERAGE

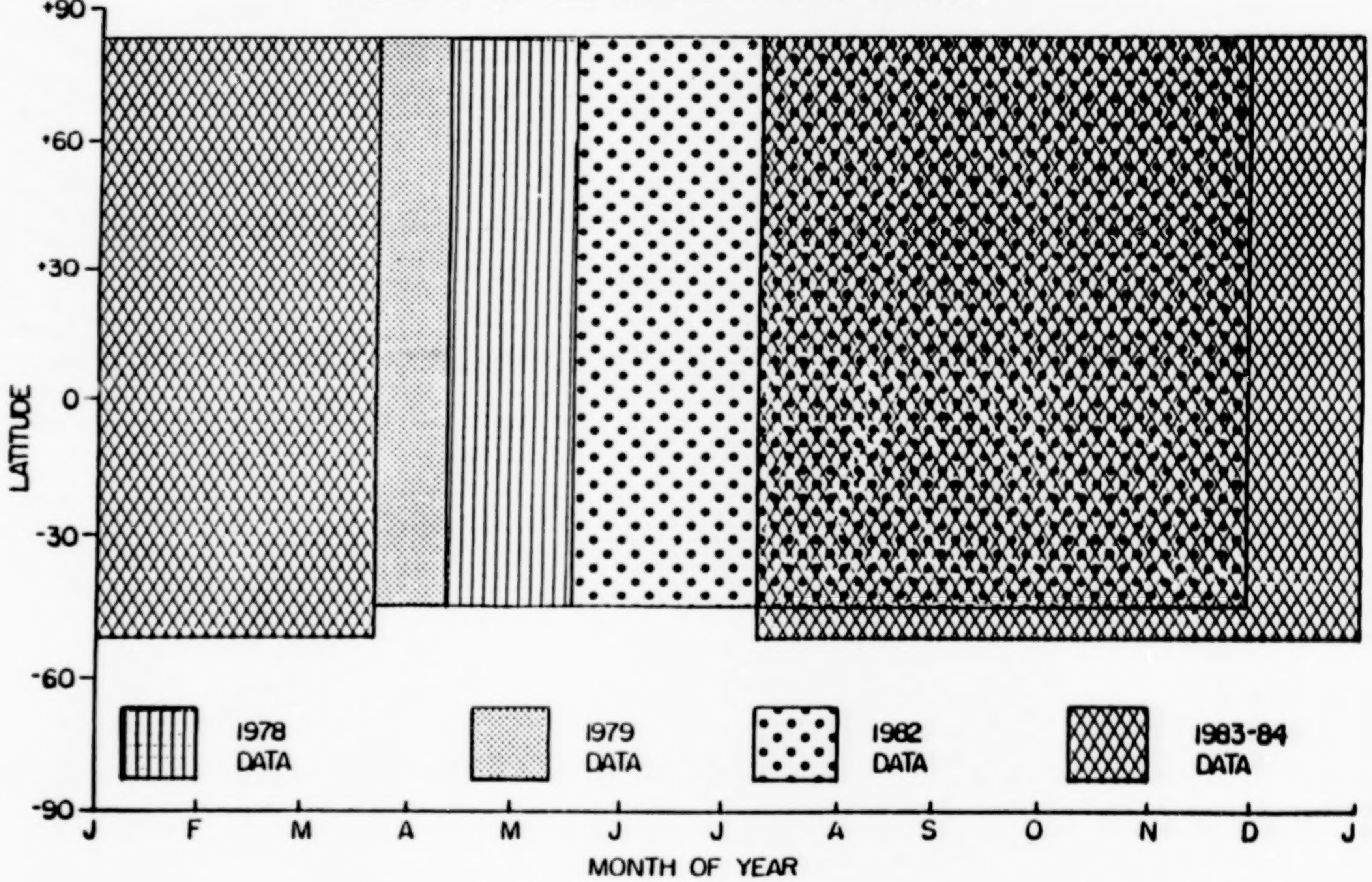
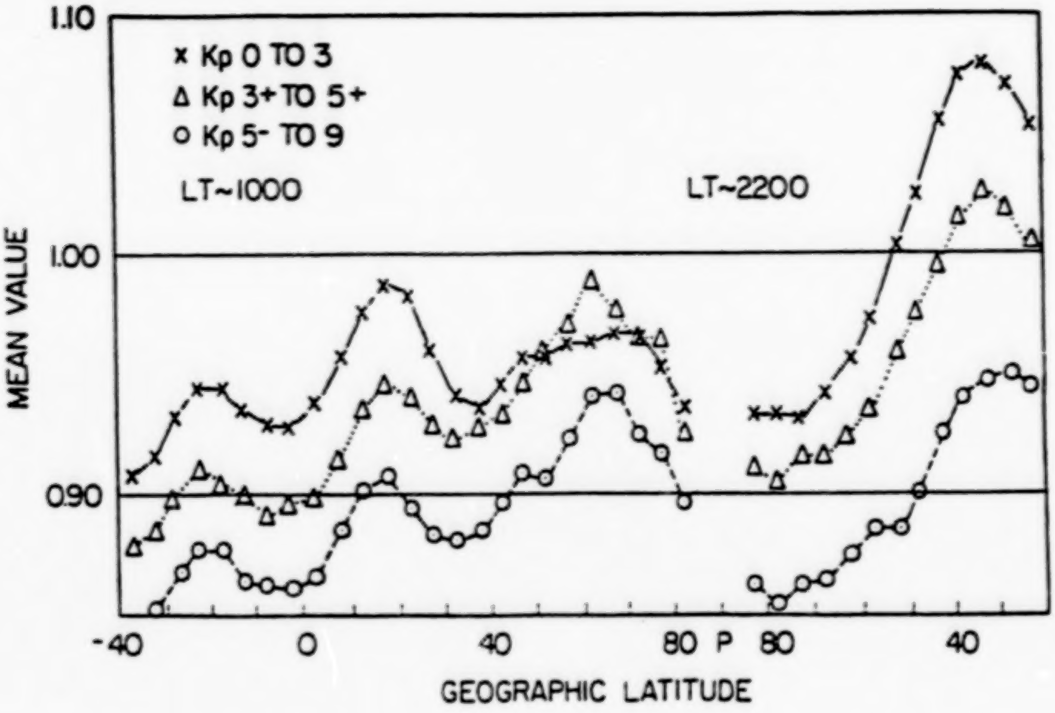
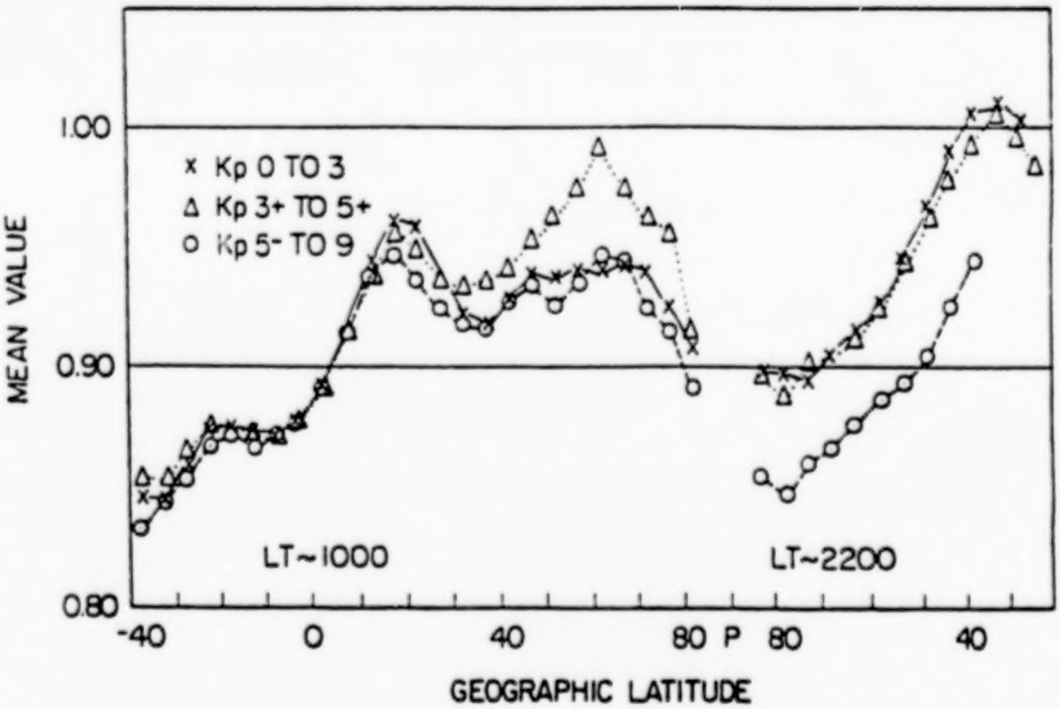


TABLE 2. ACCELEROMETER, TOTAL MASS DENSITY RATIOS TO MODELS (ALTITUDE 150-240 KM)

	AE-C		AE-D		AE-E		S3-1		S3-4		SETA-1		SETA-2	
	$\bar{R}$	σ_R	$\bar{R}$	σ_R	$\bar{R}$	σ_R	$\bar{R}$	σ_R	$\bar{R}$	σ_R	$\bar{R}$	σ_R	$\bar{R}$	σ_R
MSIS83B	1.14	15.3	1.00	16.2	1.02	13.4	1.07	14.6	0.98	11.8	0.92	9.7	0.87	11.6
MSIS83A	1.15	15.6	1.00	16.4	1.04	14.1	1.08	14.8	0.99	12.1	0.93	10.1	0.88	11.8
MSIS79	1.09	14.5	1.00	16.8	1.01	13.7	1.00	14.6	0.98	11.5	0.96	11.7	0.92	11.7
MSIS77	1.09	14.2	1.00	16.5	1.01	13.6	1.00	14.2	0.98	11.2	0.96	11.5	0.92	11.2
J77	1.08	16.2	1.01	15.7	1.01	15.4	1.04	14.3	0.94	13.7	0.88	12.6	0.89	13.9
J73	1.10	14.3	1.03	15.1	1.06	13.8	1.06	13.5	0.96	11.6	0.92	9.8	0.92	10.2
J71	1.13	14.9	1.06	15.1	1.08	15.0	1.08	13.7	0.99	12.1	0.94	9.9	0.95	10.1
J70	1.08	17.6	0.99	15.9	1.00	15.9	1.04	14.6	0.97	12.0	0.99	9.3	0.93	10.4
J64	0.97	17.3	0.89	17.0	0.91	15.4	0.92	17.8	0.90	11.6	0.99	11.1	0.88	11.3
L-H	0.98	18.2	0.87	17.1	0.86	16.4	0.94	14.9	0.93	14.6	0.99	9.9	0.91	11.4
JWB	1.04	19.5	1.02	18.8	1.02	19.6	0.99	19.6	0.86	11.0	0.90	10.4	0.82	10.9
US66	0.98	16.8	0.90	15.8	0.91	15.4	0.95	14.4	0.90	11.5	0.99	11.0	0.88	11.2
US62	0.92	28.9	0.76	30.3	0.76	29.6	0.73	32.7	0.93	17.6	1.13	12.0	0.96	15.0
DENS	1.49	20.7	1.05	19.6	0.97	22.4	1.31	19.5	0.79	19.9	0.87	14.9	0.99	15.2



Mean values of SETA-1 data to J71 model plotted as a function of geographic latitude (three Kp bins).



Mean values of SETA-1 data to MSIS83 model plotted as a function of geographic latitude (three Kp bins).

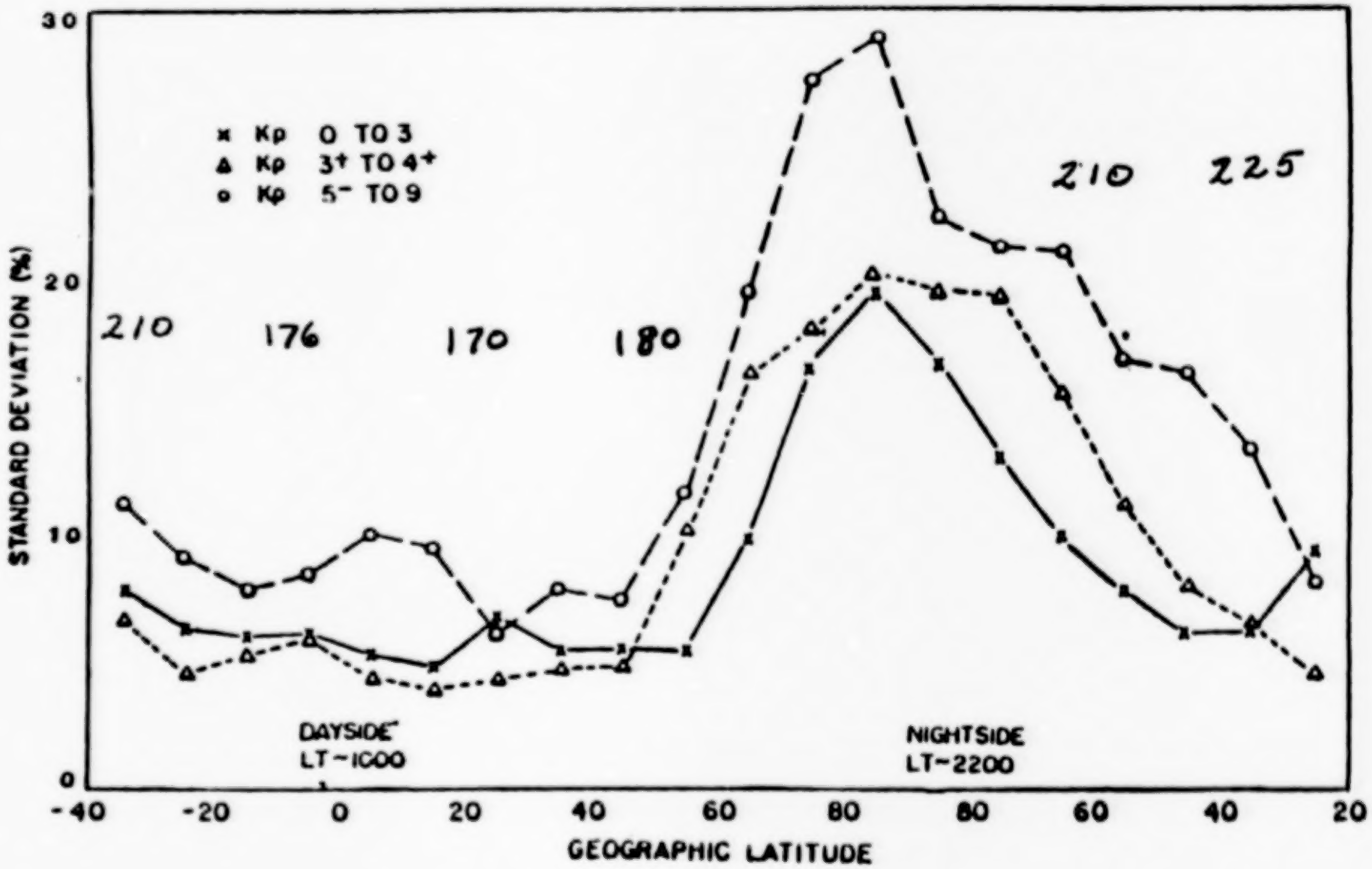


Figure 11a. Standard Deviations of Ratios of SETA-1 Density Data to J71 Model

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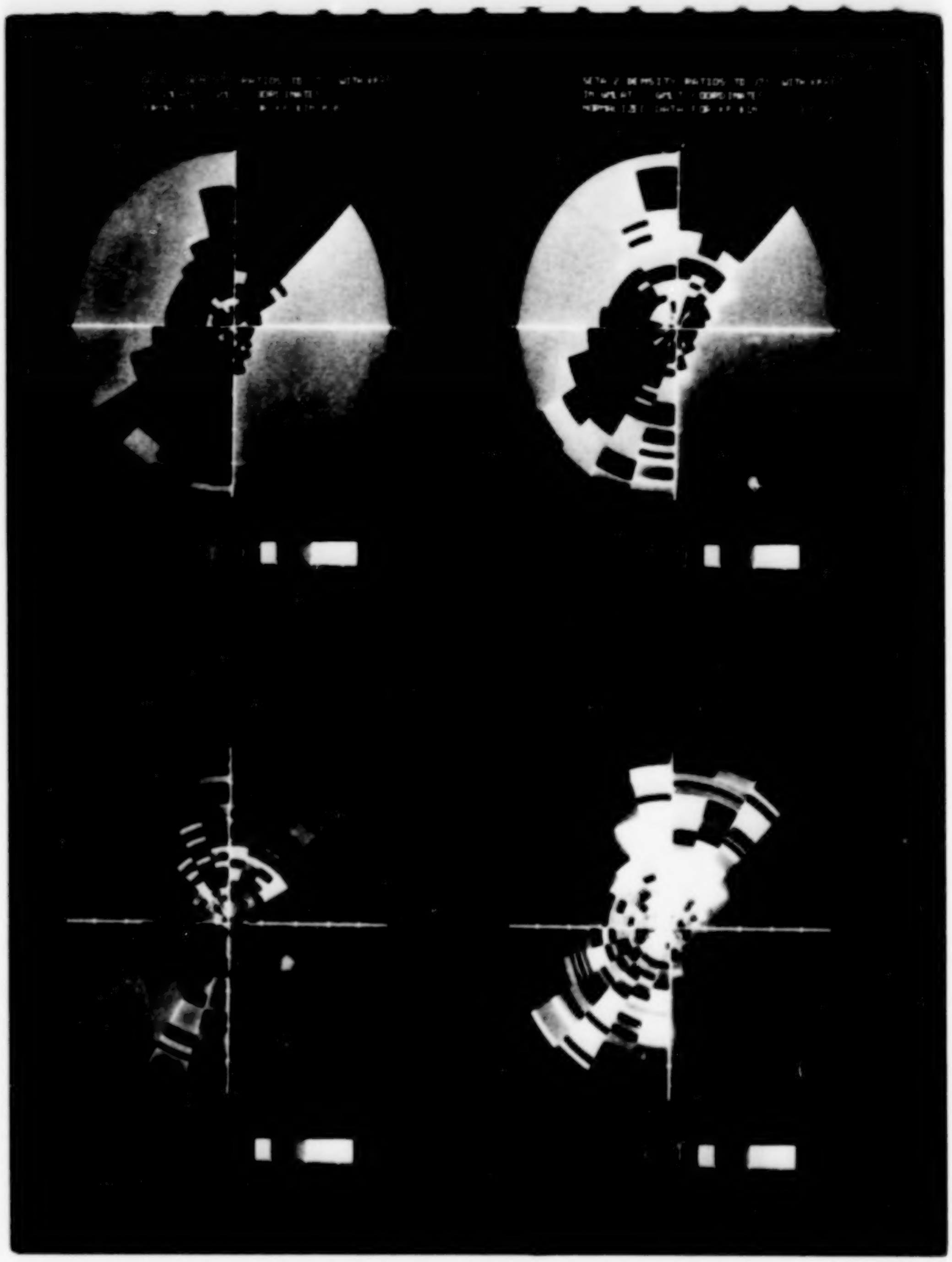

Fig. 7. SETA-1 density ratios to J71 (with Kp = 1) plotted in geomagnetic latitude - geomagnetic local time. The four Kp bins are: 0 + 1.5, > 1.5 to 3.5, > 3.5 to 5.5 and > 5.5.

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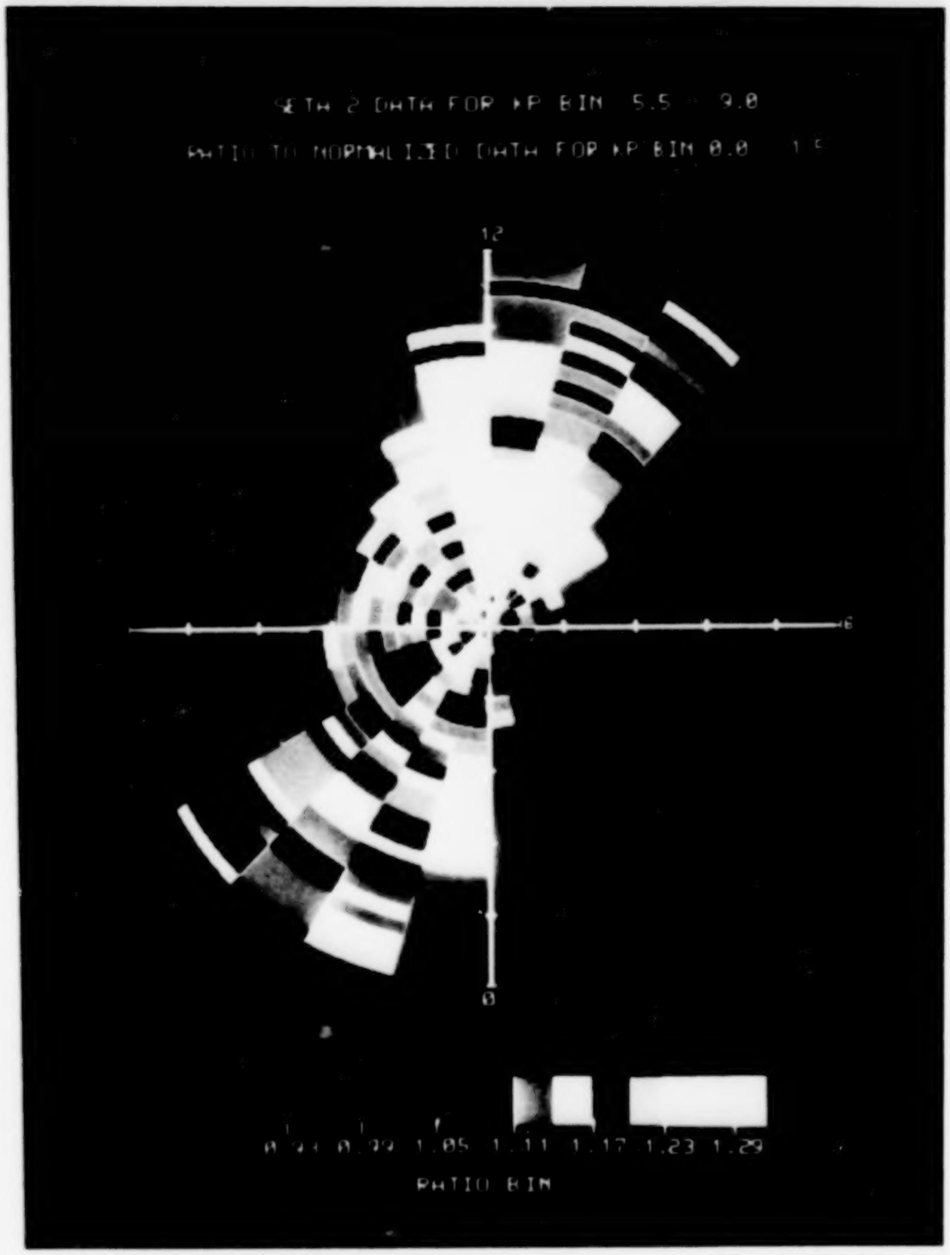

Fig. 8. Density response to geomagnetic activity calculated from the ratio of the > 5.5 Kp bin to the 0 to 1.5 Kp bin data of Fig. 7.

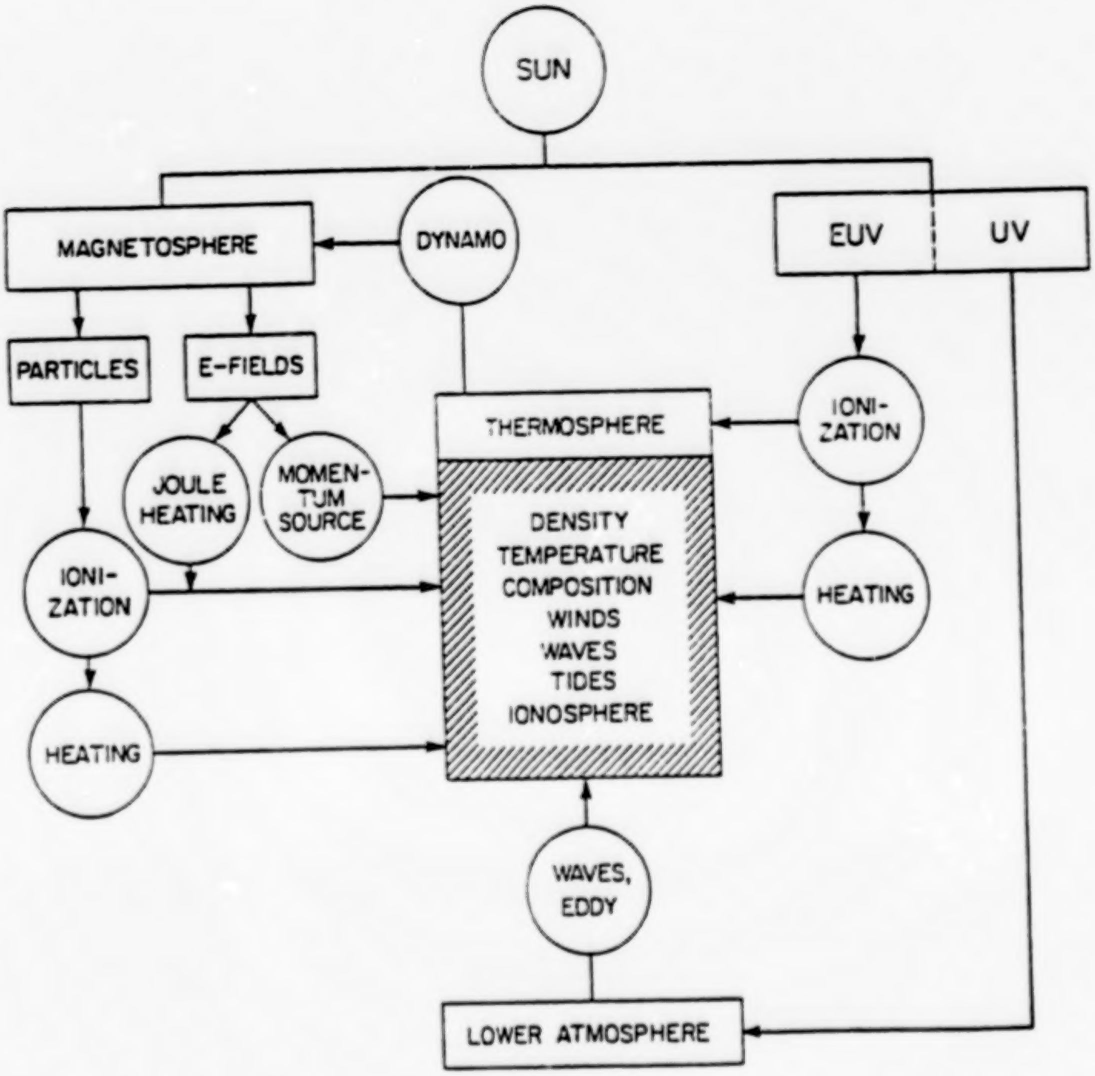
SUN
MAGNETOSPHERE
DYNAMO
EUV
UV
PARTICLES
E-FIELDS
THERMOSPHERE
IONI-ZATION
JOULE HEATING
MOMEN-TUM SOURCE
DENSITY
TEMPERATURE
COMPOSITION
WINDS
WAVES
TIDES
IONOSPHERE
IONI-ZATION
HEATING
HEATING
WAVES, EDDY
LOWER ATMOSPHERE

Fig. 9. Schematic block diagram illustrating interactions between the lower atmosphere, thermosphere and magnetosphere.

REQUIREMENTS

- DATA ANALYSIS VS. SOLAR/GEOPHYSICAL CONDITIONS
- REALISTIC ATMOSPHERIC HEATING INDICATORS
- DYNAMIC MODEL IMPROVEMENTS
- COORDINATED SATELLITE PROGRAM FOR LOWER THERMOSPHERE DYNAMICS

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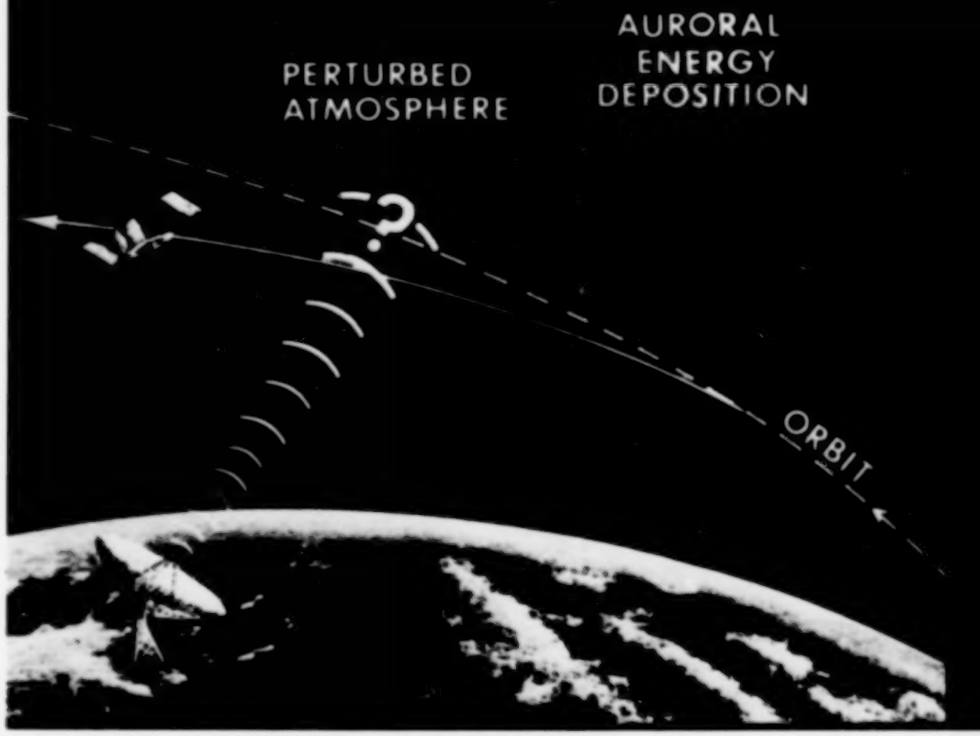
ATMOSPHERIC DENSITY SPECIFICATION (ADS)
AFGL-504
CONCEPT



OBJECTIVE

- PREDICT SATELLITE DRAG AND ATMOSPHERIC DENSITY PERTURBATIONS.
- RELATE IONOSPHERIC ANOMALIES TO C^3 I SYSTEMS DISRUPTIONS.

DESCRIPTION

- GLOBAL DETERMINATION OF:
  - AERODYNAMIC DRAG
  - ATMOSPHERIC DENSITY
  - NEUTRAL COMPOSITION
  - HORIZONTAL WINDS
  - TEMPERATURE
  - IONOSPHERIC COMPOSITION
- RESULTANT DATA BASE USED TO DEVELOP NEW DYNAMIC MODELS FOR OPERATIONAL ORBIT DETERMINATION AND PREDICTION AND FOR COMMAND, CONTROL AND SURVEILLANCE SYSTEMS.

SOLAR ACTIVITY - GEOMAGNETIC INDICES

Chairperson: J. Joselyn

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FORECASTS OF SOLAR AND GEOMAGNETIC ACTIVITY

JoAnn Joselyn, NOAA Environmental Research Laboratories
Space Environment Laboratory

Forecasts of solar and geomagnetic activity are critical since these quantities are such important inputs to the thermospheric density models. At the moment, a key question is "When will the next solar maximum be, and how large will it be?" At this time in the history of solar science there is no way to make such a forecast from first principles. Physical theory applied to the sun is developing rapidly, but is still primitive. Techniques used for forecasting depend upon the observations over about 130 years, which is only twelve solar cycles. (The solar sunspot cycle period is about eleven years, but shows considerable variability. The number of cases available for study is too small for a reliable statistical analysis.) It has been noted that even-numbered cycles systematically tend to be smaller than the odd-numbered ones by about 20 percent. Another observation (Sargent) is that for the last 12 cycle pairs, an even-numbered sunspot cycle looks rather like the next odd-numbered cycle, but with the top cut off. These observations are examples of approximate periodicities that forecasters try to use to achieve some insight into the nature of an upcoming cycle. Another new and useful forecasting aid is a correlation that has been noted between geomagnetic indices and the size of the next solar cycle.

Geomagnetic activity tends to correlate with solar activity. There appears to be an 88 year periodicity (the Gleissberg Cycle). Other quasi-periodicities can be partially accounted for by noting that during even cycles, high aa is primarily due to coronal holes, while during odd cycles it is due to solar flare activity. Based on these and similar considerations, in the mid 1990's we expect that aa<10 70-145 days per year (quiet), 10<aa<50 22-55 days/year with K's 5 or greater. As a function of season of the year, on the average there is more geomagnetic activity during the equinoxes than during the solstices.

Now to forecasts: We think that it is very unlikely that the next solar minimum will occur before June, 1986. Our best guess is July, 1987. We are unwilling to say when the next maximum will occur, but the best estimate for the time of the next maximum would probably be July of 1991. The next solar maximum looks like around 150 for F10.7.

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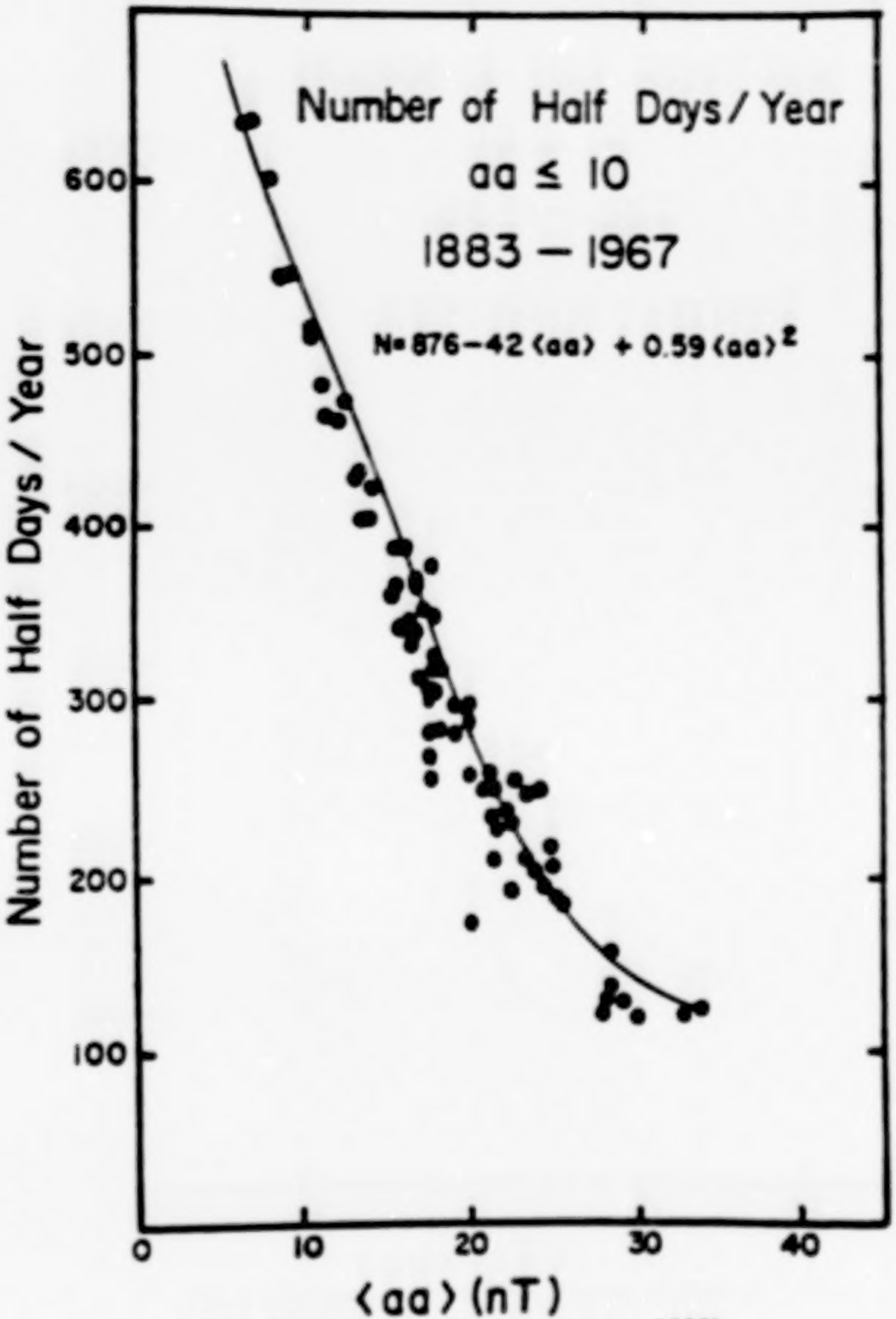

After Feynman and Gu (in Press, 1985)

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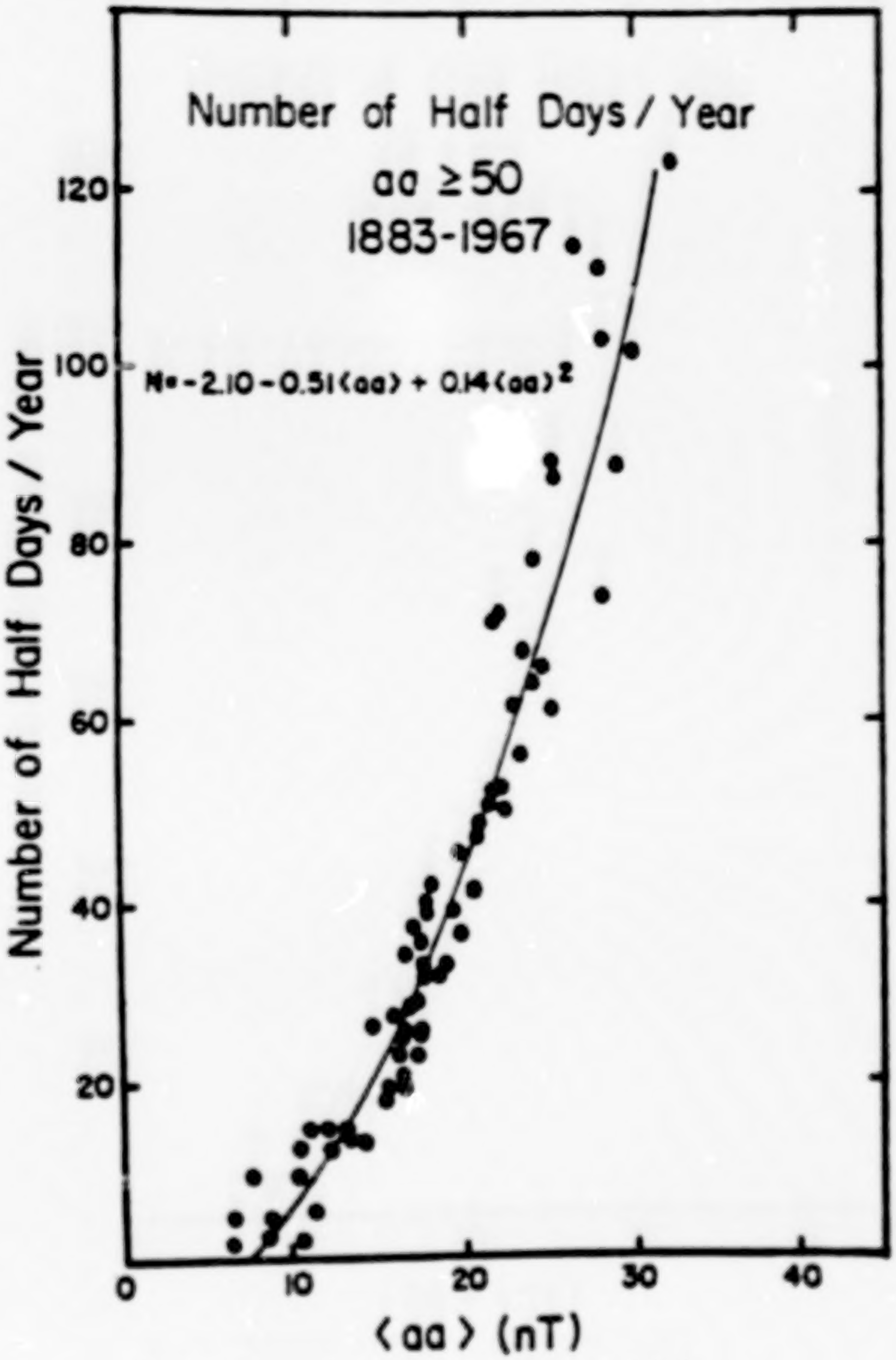
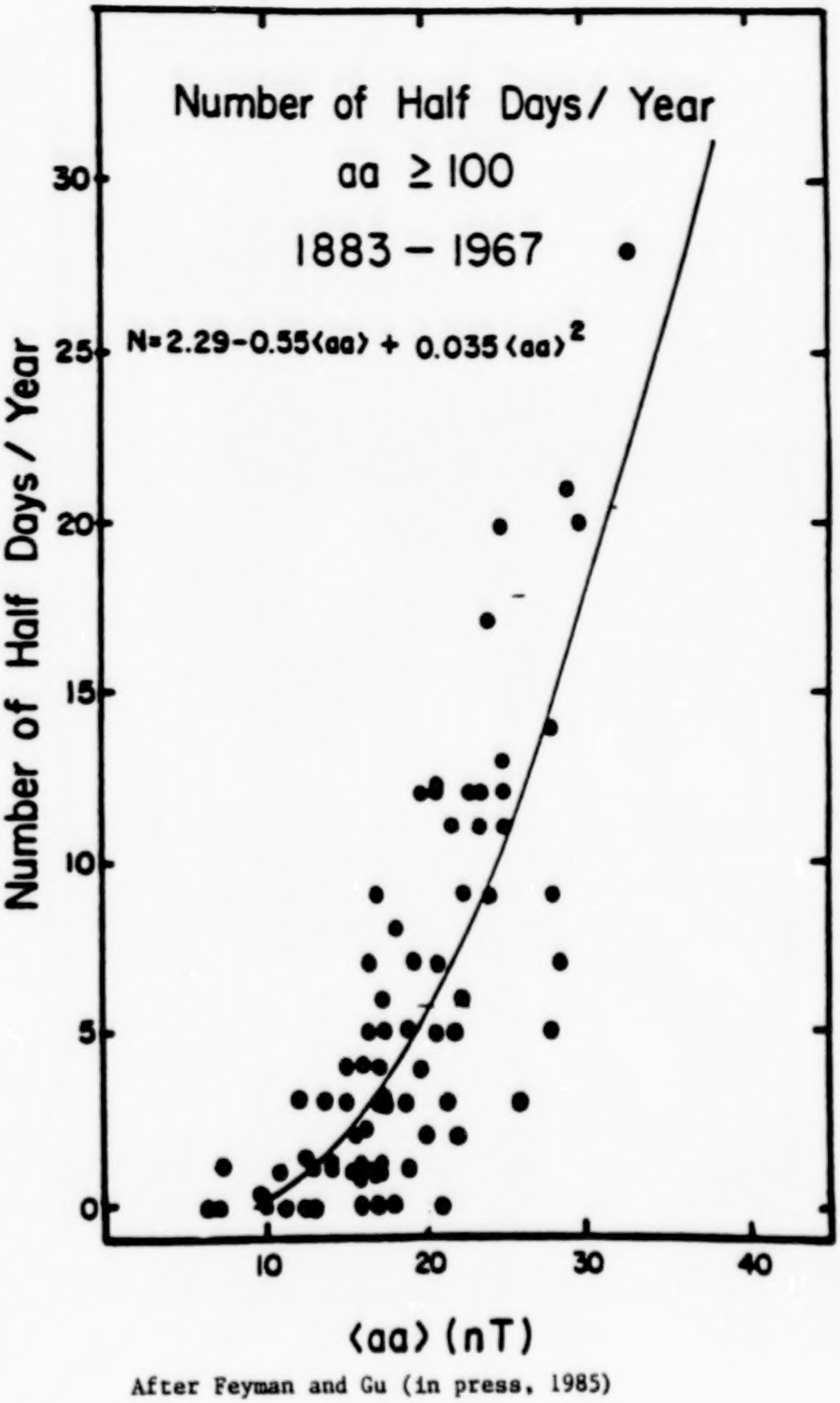
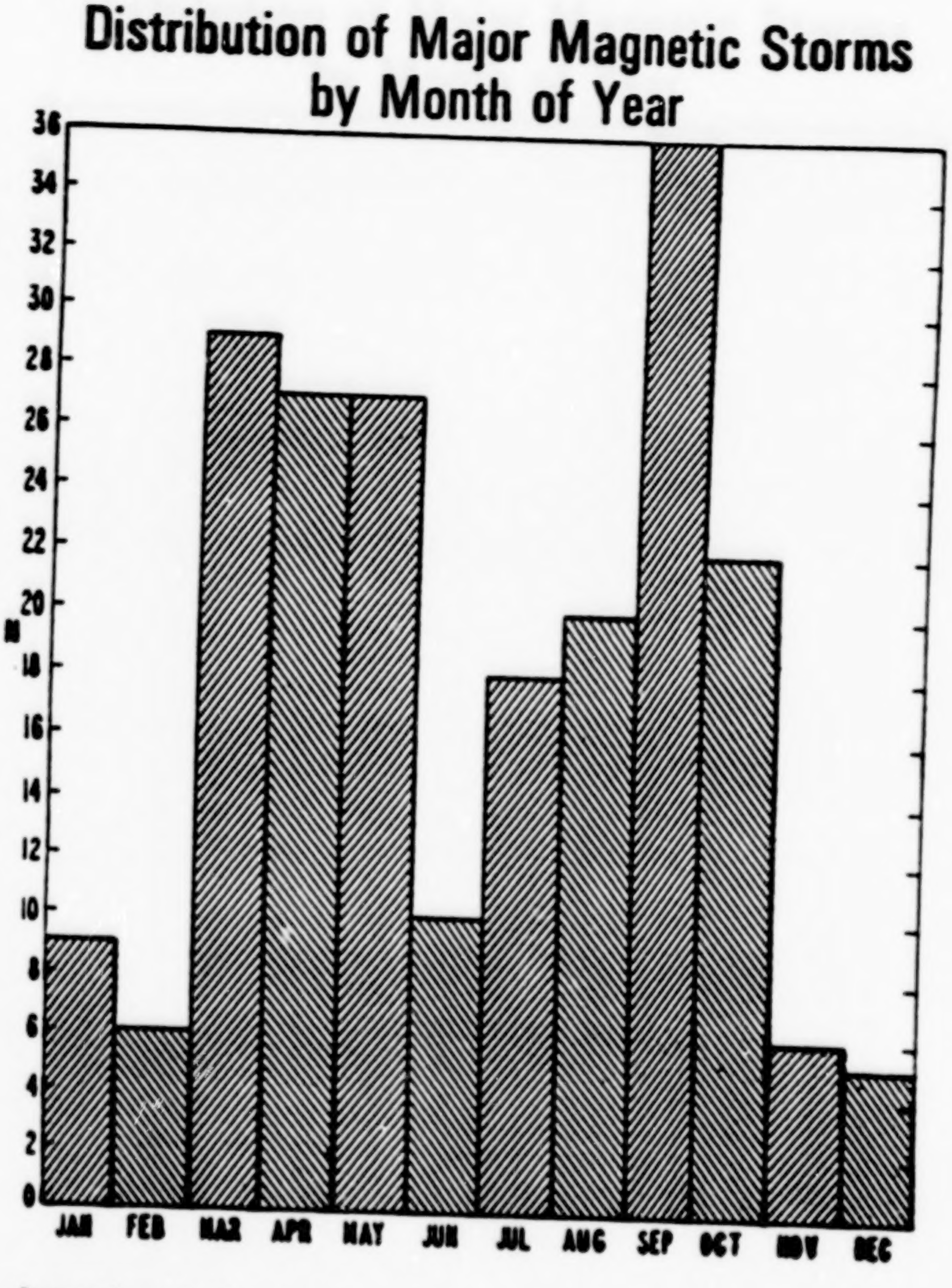


After Feynman and Gu (in press, 1985)



After Feyman and Gu (in press, 1985)



28. Seasonal variation in cumulative number of truly large storms, 1932-1980. (Allen, 1982)

(JGR, 1982)

Feynman: Geomagnetic and Solar Wind Cycles, 1900-1975

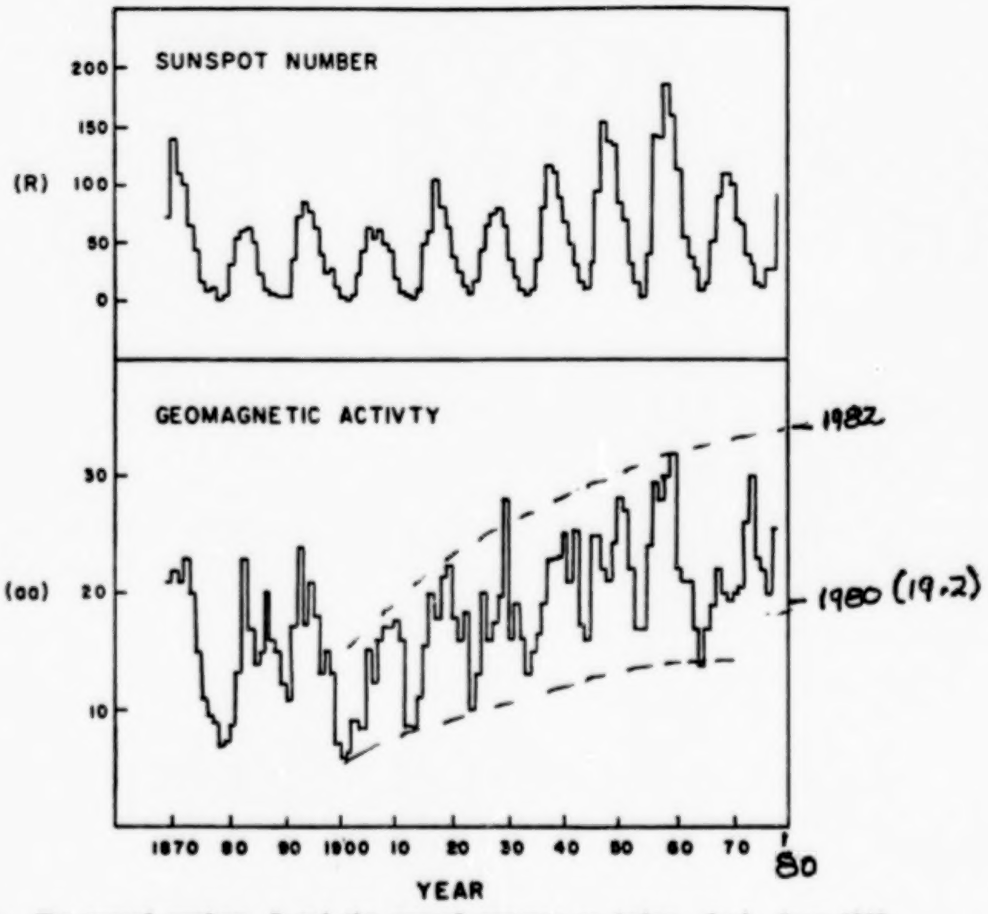


Fig. 1. The annual number, R and the annual average aa index, (aa), from 1868 to 1975. (aa) is measured in units of nanoteslas.

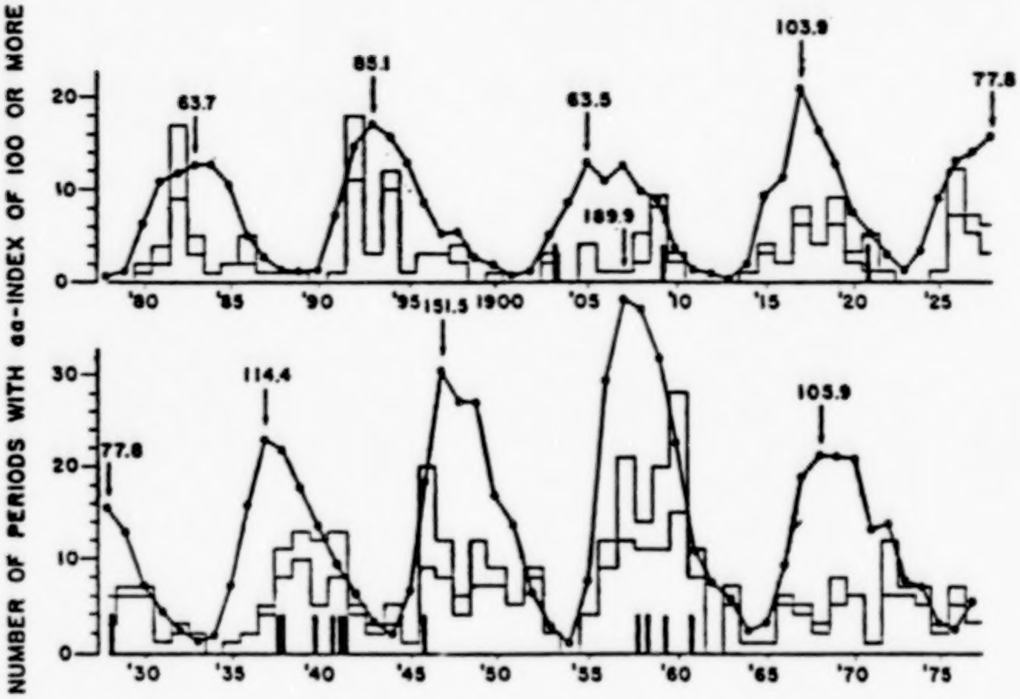


Figure 2. Bar chart showing the number of half-day periods each year when the aa-index equalled or exceeded 100 gammas. Shaded levels indicate the number of separate high-category major geomagnetic storms in a given year (some storms involve several consecutive half-day periods). Heavy vertical lines indicate super storms (where the half-day value equalled or exceeded 350 gammas). Annual mean sunspot numbers are also shown with maximum values specified for each cycle.

SARGENT (1979)

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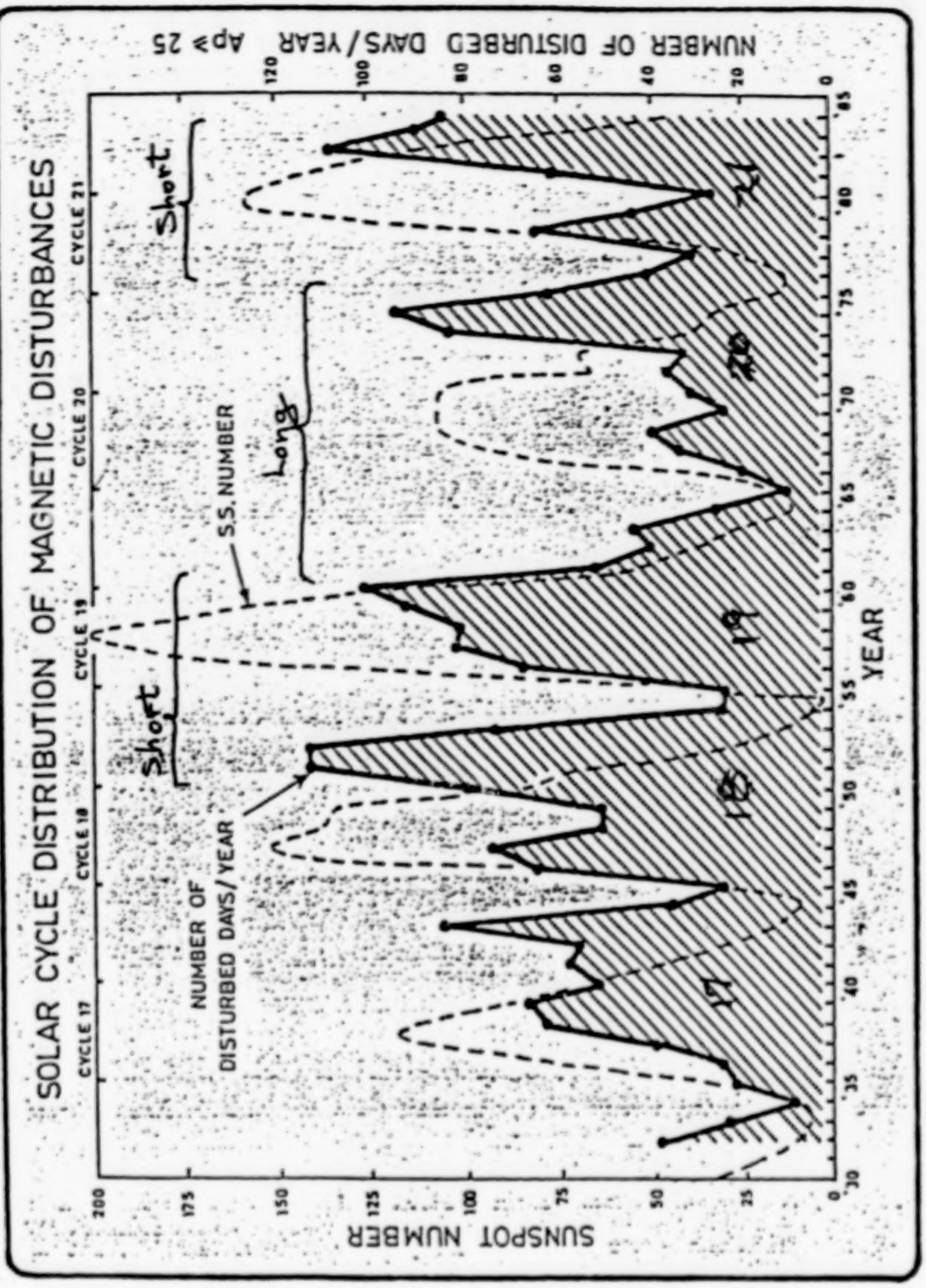

From IPS Solar-Geophysical Summary for Apr. 1985

Figure:
The frequency of occurrence of geomagnetic disturbances is not constant but varies from year-to-year in a complicated manner. The figure shows the number of magnetically disturbed days in each year since 1932 (cross-hatched area). For comparison the variation of the sunspot number is also shown (dashed line). It is evident from the figure that there is some tendency for a peak of disturbances to occur near the peak of the solar cycle. However the greatest number of disturbances often occurs during the declining phase of the solar cycle

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NASA/MSFC PREDICTION TECHNIQUES

Robert E. Smith, Marshall Space Flight Center

The NASA/MSFC method of forecasting is more formal than NOAA's. The data is smoothed by the Lagrangian method and linear regression prediction techniques are used. The solar activity period is fixed at 11 years--the mean period of all previous cycles. Interestingly, our present prediction for the time of the next solar minimum is February or March of 1987, which, within the uncertainties of two methods, can be taken to be the same as the NOAA result.

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MSFC SOLAR ACTIVITY PREDICTION TECHNIQUE

- DATABASE
  - SOLAR CYCLES 1-21
  - DATA SMOOTHED BY LAGRANGIAN METHOD
  - 132 EQUALLY SPACED DATA POINTS IN EACH CYCLE
  - 2 SEPARATE BASES
    - MAX TO MAX
    - MIN TO MIN
- PREDICTION TECHNIQUE
  - LINCOLN-McNISH LINEAR REGRESSION TECHNIQUE USING ONE DATA POINT
  - RANK DATA IN 40 CLASS INTERVALS AT EACH TIME INCREMENT
  - FIRST CLASS INTERVAL THAT CONTAINS DATA IS THE 2.5 PRECENTILE
  - LAST CLASS INTERVAL THAT CONTAINS DATA IS THE 97.5 PERCENTILE
  - PERIOD IS FIXED AT 11 YEARS (132 DATA POINTS)
  - MAX TO MAX AND MIN TO MIN PREDICTIONS

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MIDDLE ATMOSPHERE MODEL USERS

Chairperson: J. Gamble

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USERS OF MIDDLE ATMOSPHERE MODELS
REMARKS

Joe Gamble, NASA/Johnson Space Center

The procedure followed for shuttle operations is to calculate descent trajectories for each potential shuttle landing site using the Global Reference Atmosphere Model (GRAM) to interactively compute density along the flight path 100 times to bound the statistics. The purpose is to analyze the flight dynamics, along with calculations of heat loads during re-entry. The analysis program makes use of the modified version of the Jacchia-70 atmosphere, which includes He bulges over the poles and seasonal latitude variations at lower altitudes. For the troposphere, the 4-D model is used up to 20 km, Groves from 30 km up to 90 km. It is extrapolated over the globe and faired into the Jacchia atmosphere between 90 and 115 km. Since data on the Southern Hemisphere was lacking, what was done was that the data was flipped over and lagged 6 months. Remarkably, this procedure seems to work quite well.

Sometimes when winds are calculated from pressure data in the model there appear to be discontinuities. Modelers indicated that the GRAM was not designed to produce winds, but good wind data is needed for the landing phase of shuttle operations. It was remarked that use of atmospheric models during re-entry is one application where it is obvious that a single integrated atmosphere model is required.

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	J. GAMBLE	11/20/85

USERS SESSION

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EMPHASIS OF SESSION

- HOW MODELS ARE BEING UTILIZED (JSC EMPHASIS IS ON GRAM)
- MODEL CHARACTERISTICS THAT ARE POSING POTENTIAL PROBLEMS TO TRAJECTORY CONTROL
- SENSITIVITY TO ATMOSPHERIC PERTURBATIONS, DEFINITION OF CRITICAL AREAS

	J. GAMBLE	11/20/85

AGENDA

- OVERVIEW OF JSC GRAM ACTIVITIES
- SPACE SHUTTLE APPLICATIONS - KENT JOOSTEN/JSC, STEVE MCCARTY/MDC
- AOTV APPLICATIONS - OLIVER HILL/JSC
- CORRELATION WITH SHUTTLE DATA, AOTV IMPLICATIONS - JOE GAMBLE/JSC
- OTHER PREPARED COMMENTS
- OPEN DISCUSSION
- SPACE SHUTTLE RESULTS - JOHN FINDLAY/FLIGHT MECHANICS AND CONTROL

J. GAMBLE

11/20/85

OVERVIEW OF JSC GRAM ACTIVITIES

- GRAM IS BEING UTILIZED BY SEVERAL JSC ORGANIZATIONS
  - MISSION OPERATIONS DIRECTORATE - SHUTTLE ENTRY SIMULATIONS
  - MISSION SUPPORT DIRECTORATE - AOTV ANALYSIS
  - ENGINEERING DIRECTORATE - CORRELATION WITH SHUTTLE RESULTS, APPLICATION TO AOTV

J. GAMBLE
11/20/85

CORRELATION WITH SHUTTLE ENTRY DATA/AOTV CONCERNS

	J. GAMBLE	11/20/85

- JSC ADVANCED PROGRAMS OFFICE HAS A THREE YEAR RTOP TO INVESTIGATE THE ATMOSPHERIC DENSITY DERIVED FROM THE SHUTTLE ENTRY FLIGHTS.
    - NATIONAL WEATHER SERVICE IS COORDINATING A SOUNDING ROCKET PROGRAM ALONG THE SHUTTLE ENTRY TRACK AND PROVIDING THEIR BEST ESTIMATE OF THE ATMOSPHERIC PROPERTIES FOR THE ENTRY PROFILE.
    - JOHN FINDLAY OF FLIGHT MECHANICS AND CONTROL IS PROVIDING ANALYSIS OF THE ENTRY DATA
- GRAM IS BEING UTILIZED FOR SIMULATIONS FOR AOTV PROGRAM
    - GRAM IS TIED INTO THE SIMULATION REAL TIME RATHER THAN FIRST GENERATING A ATMOSPHERE PROFILE OFF LINE FOR LATER USE IN THE SIMULATION.

	J. GAMBLE	11/20/85

SUMMARY

- GRAM RESULTS APPEAR CAPABLE OF REPRODUCING DENSITY PROFILES OBSERVED DURING THE SHUTTLE ENTRY FLIGHTS
  - PRIMARY CONCERN IS ABOUT THE CONFIDENCE IN THE STATISTICS OF THE GRAM RANDOM PERTURBATION MODEL. I.E. IS THE 3-SIGMA CASE REALLY 3-SIGMA, 2.5-SIGMA, 3.5-SIGMA
- MAGNITUDE OF DENSITY GRADIENTS ARE A MAJOR CONCERN FOR THE AOTV
  - CURRENT PRELIMINARY DESIGN EFFORTS ARE CONSIDERING MAXIMUM GRADIENTS OF 20-30% OCCURING OVER 1-3 KM ALTITUDE
  - LATITUDE EFFECTS ARE CRITICAL TO THE AOTV - IF DENSITY GRADIENTS OBSERVED AT MORE NOTHERN LATITUDES WERE POSSIBLE AT THE LOWER LATITUDES, THE DESIGN OF THE AOTV COULD BE SIGNIFICANTLY EFFECTED

	J. GAMBLE	11/20/85

- CORRELATION OF GRAM WITH SHUTTLE ENTRY RESULTS
  - IN A SERIES OF 20-50 GRAM RANDOM PERTURBATION RUNS IN THE 30-90 KM ALTITUDE RANGE, AT LEAST ONE RUN WILL YIELD DENSITY CHARACTERISTICS SIMILAR TO THOSE OBSERVED DURING THE SHUTTLE ENTRY.
    (QUALITATIVE EVALUATION)
  - THE SHUTTLE DEVIATIONS FROM MODEL MEAN VALUES (62,76 STD) WILL ALWAYS BE EXCEEDED BY THE ENVELOPE RESULTING FROM A SERIES OF GRAM RUNS.
  - THE AMPLITUDE OF SHUTTLE OBSERVED DENSITY GRADIENTS WILL ALWAYS BE EXCEEDED DURING A SERIES OF GRAM RUNS.

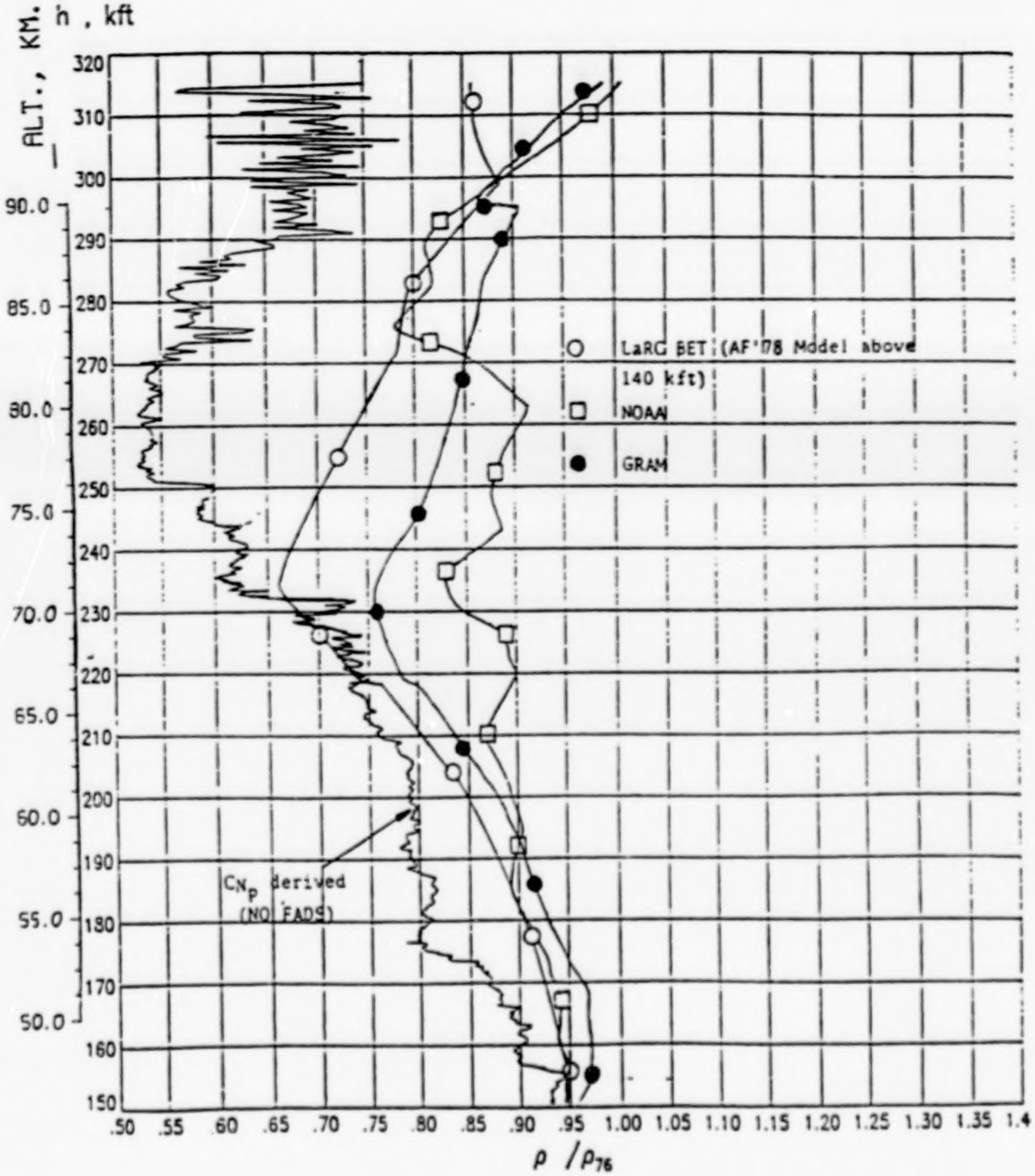
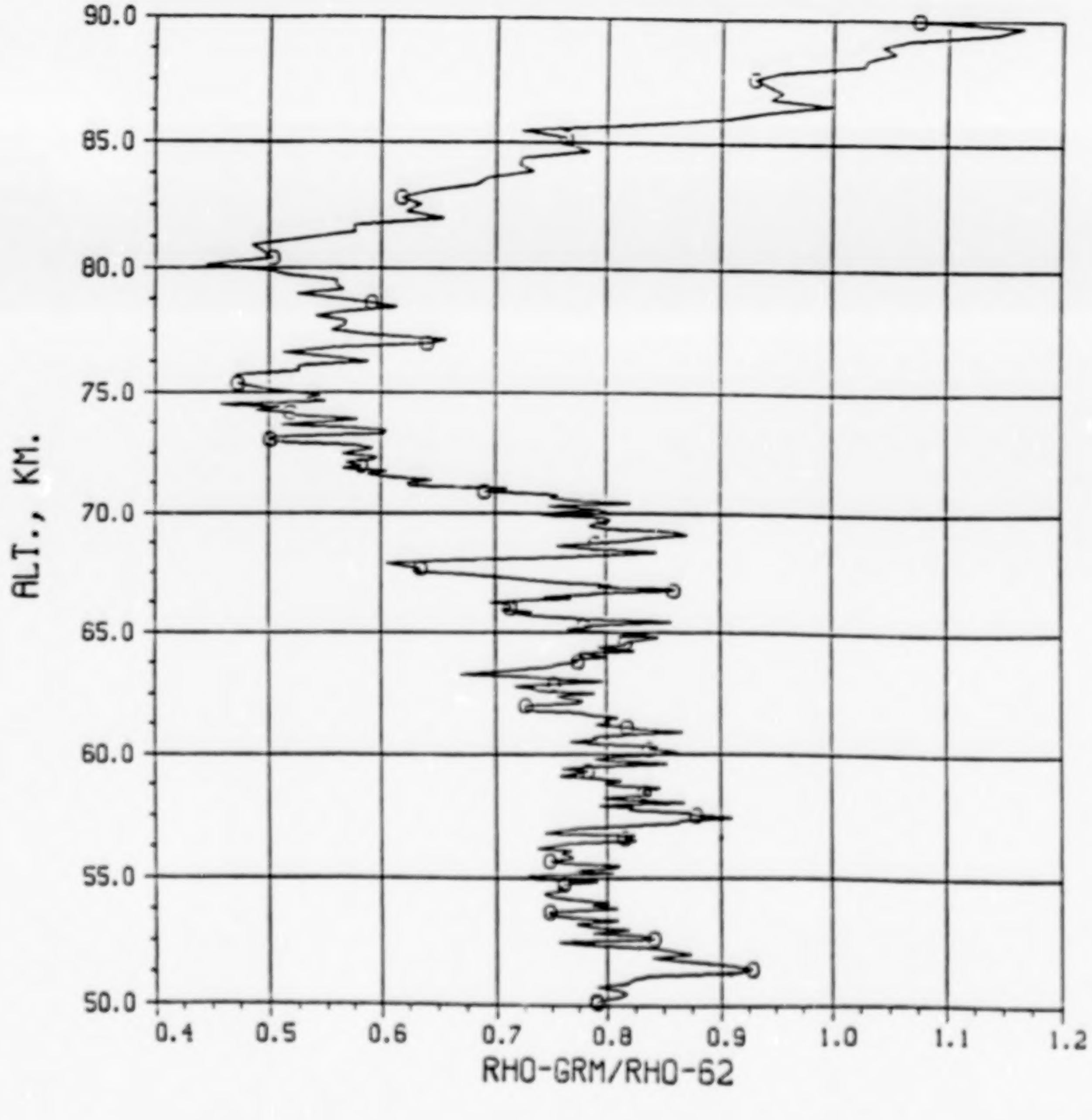


Figure A-9. STS-9 (December) density comparisons

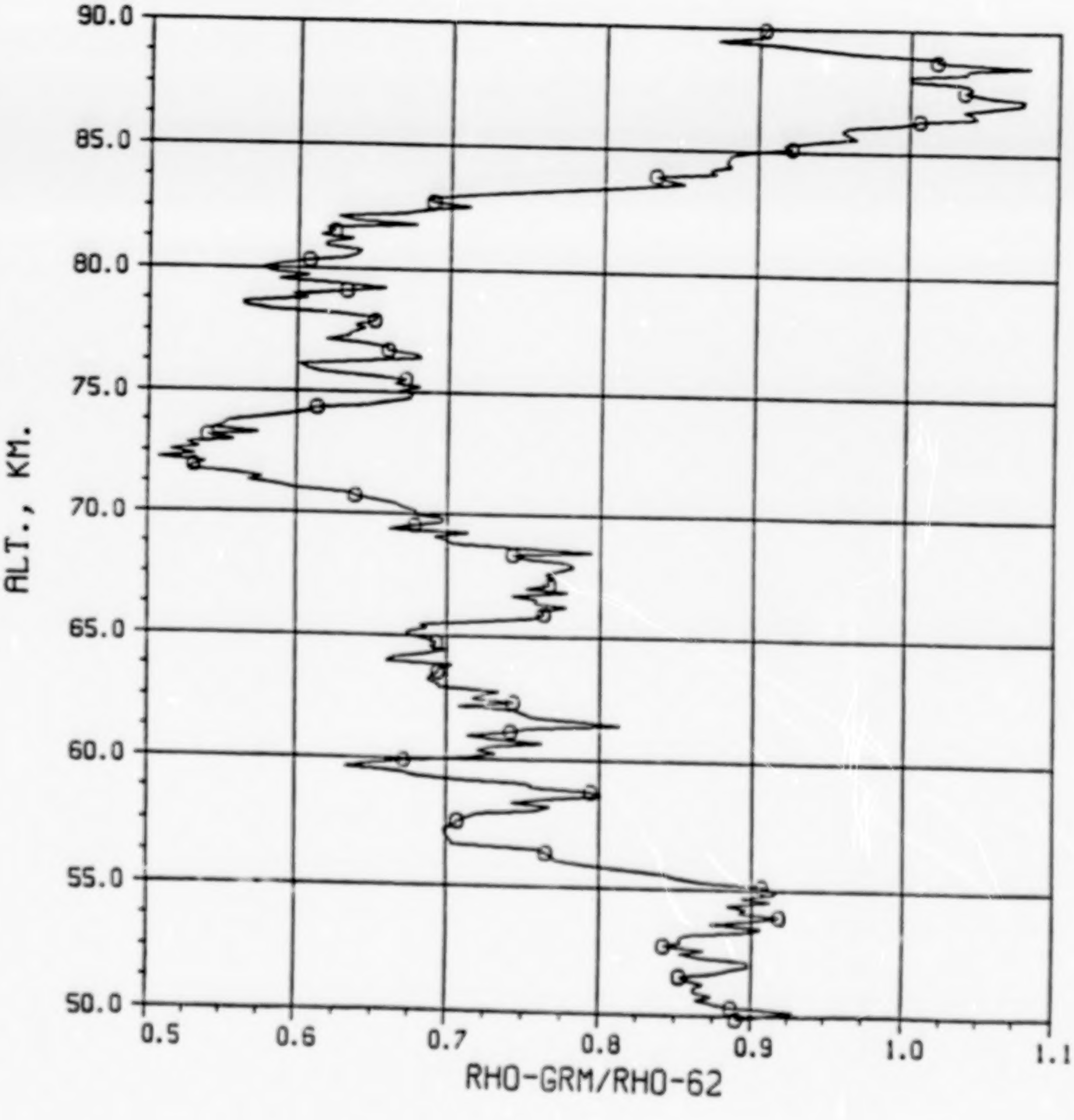
STS-9 GRAM Simulation

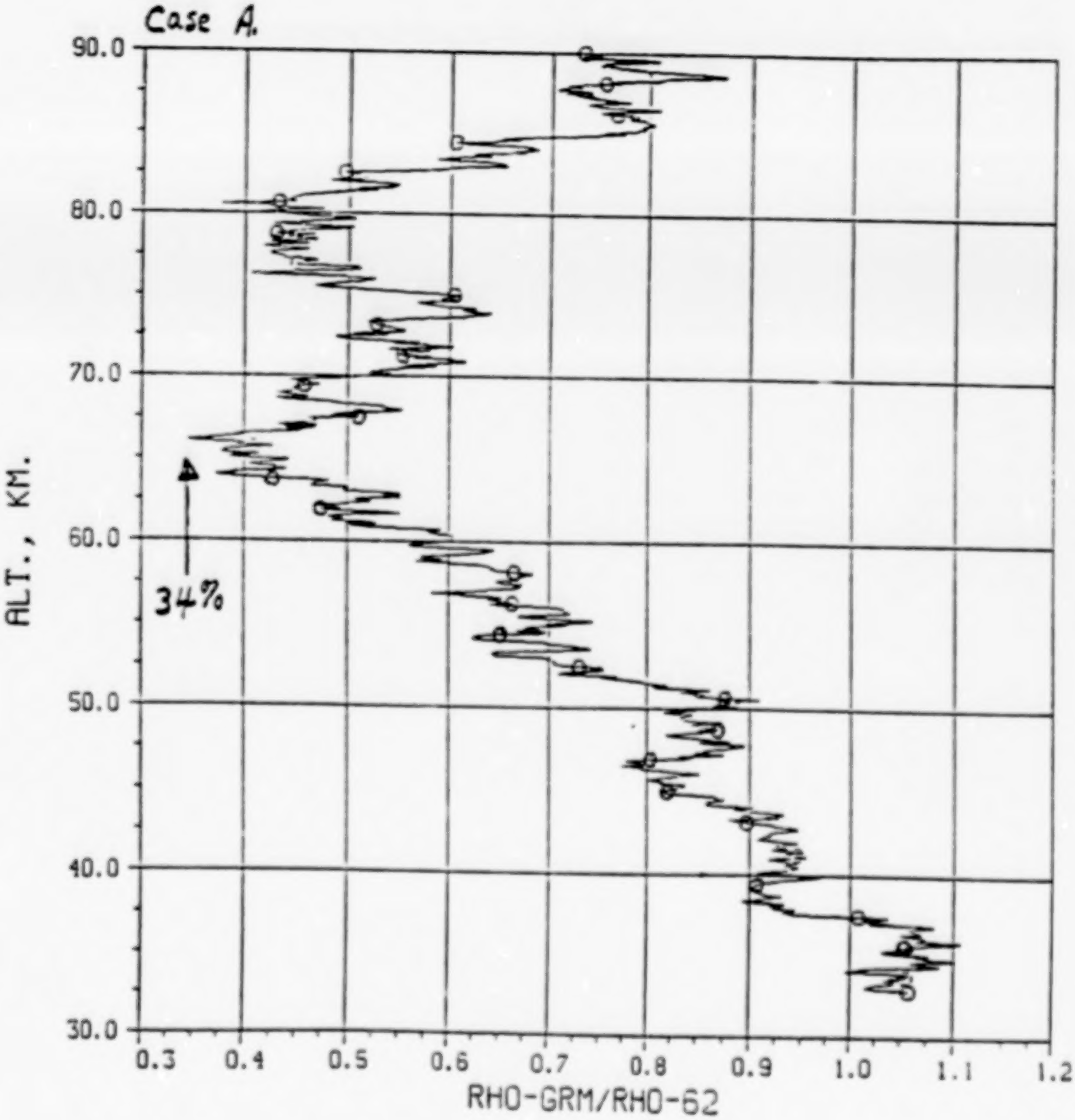
December -57° Latitude



STS-9 GRAM Simulation

December - 57° Latitude

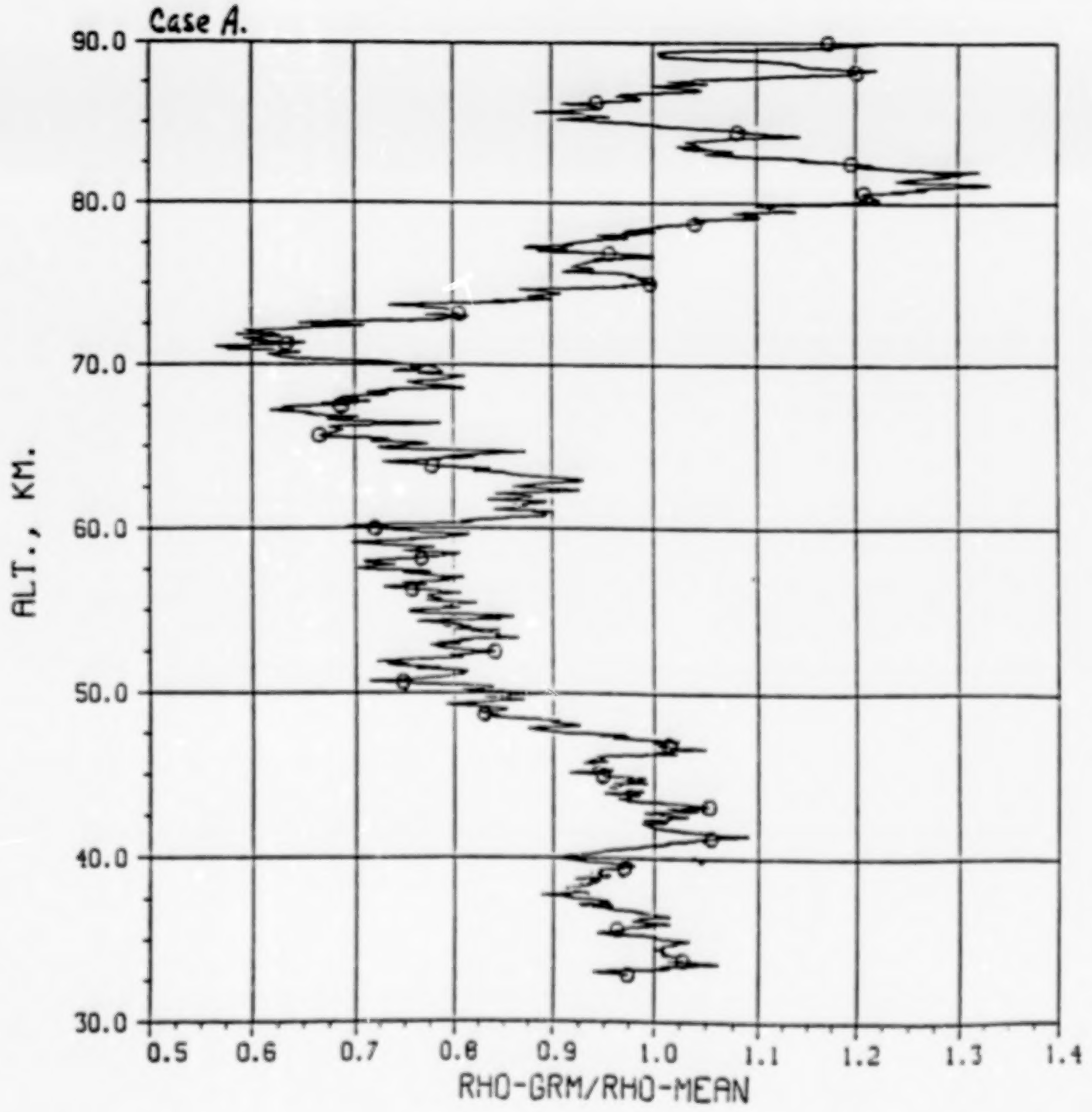




STS-9 GRAM Simulation

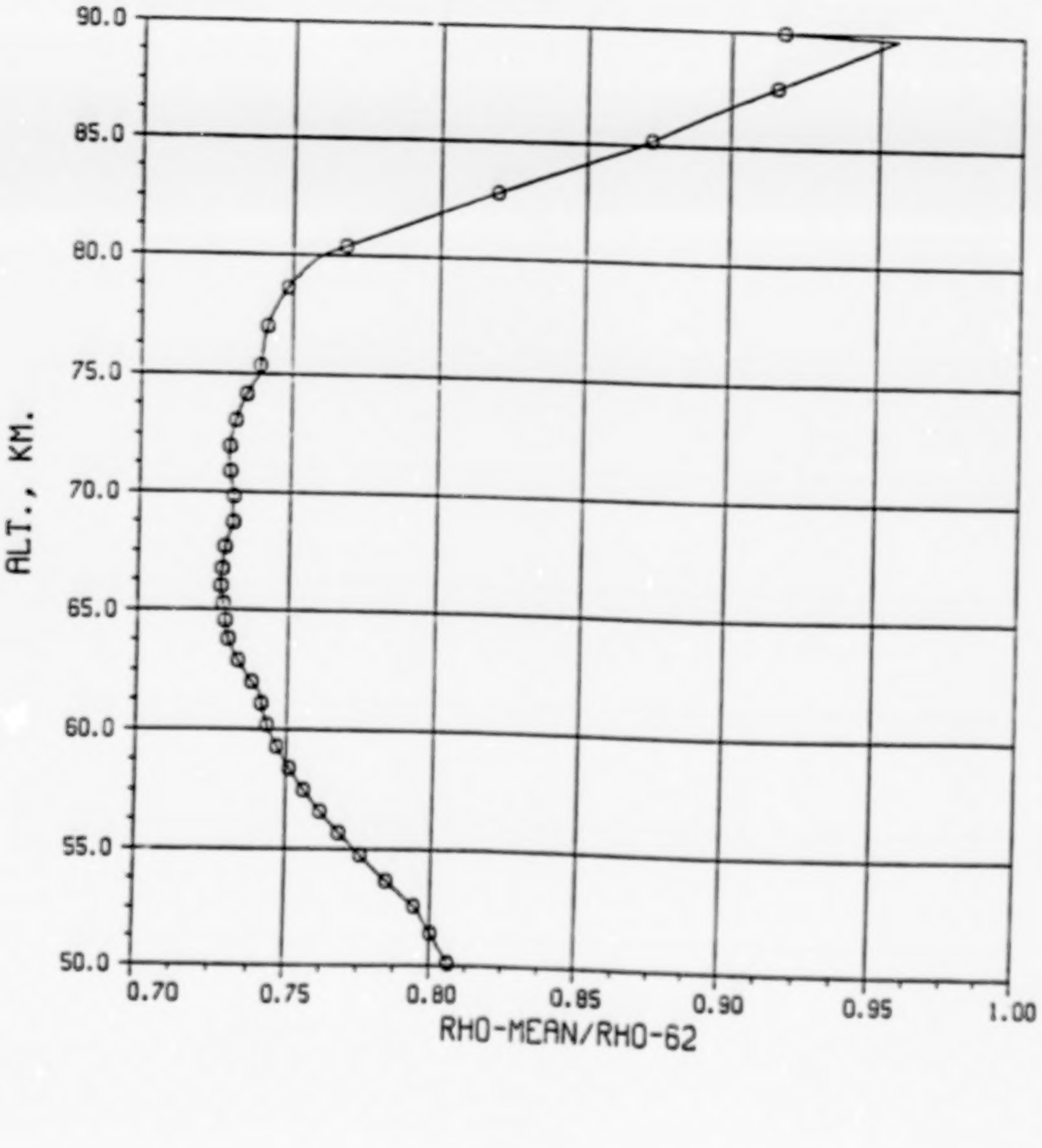
December - 57° Latitude

STS-9 GRAM Simulation
December - 57° Latitude



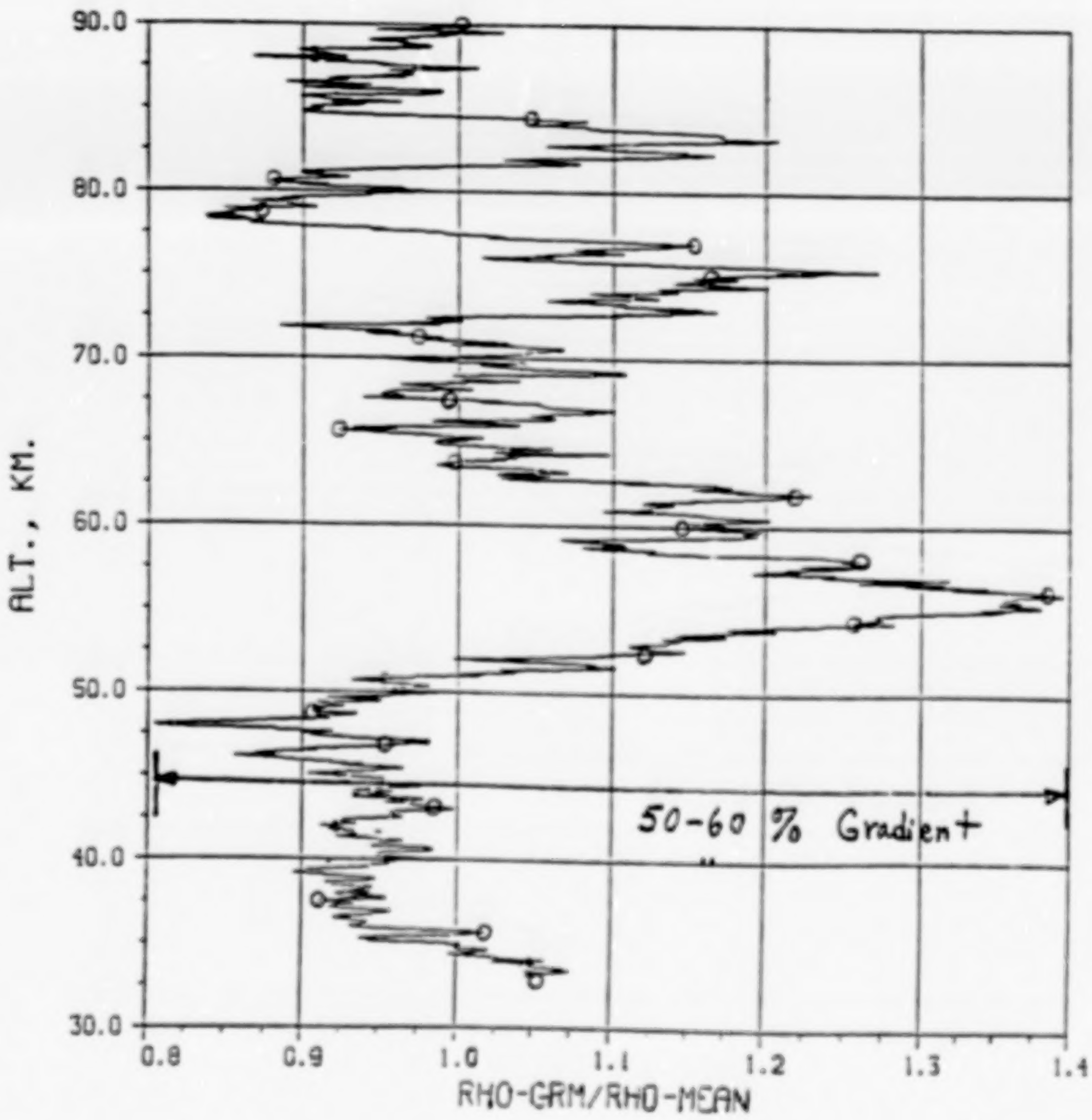
STS-9 GRAM Simulation

December - 57° Latitude



STS-9 GRAM Simulation

December - 57° Latitude



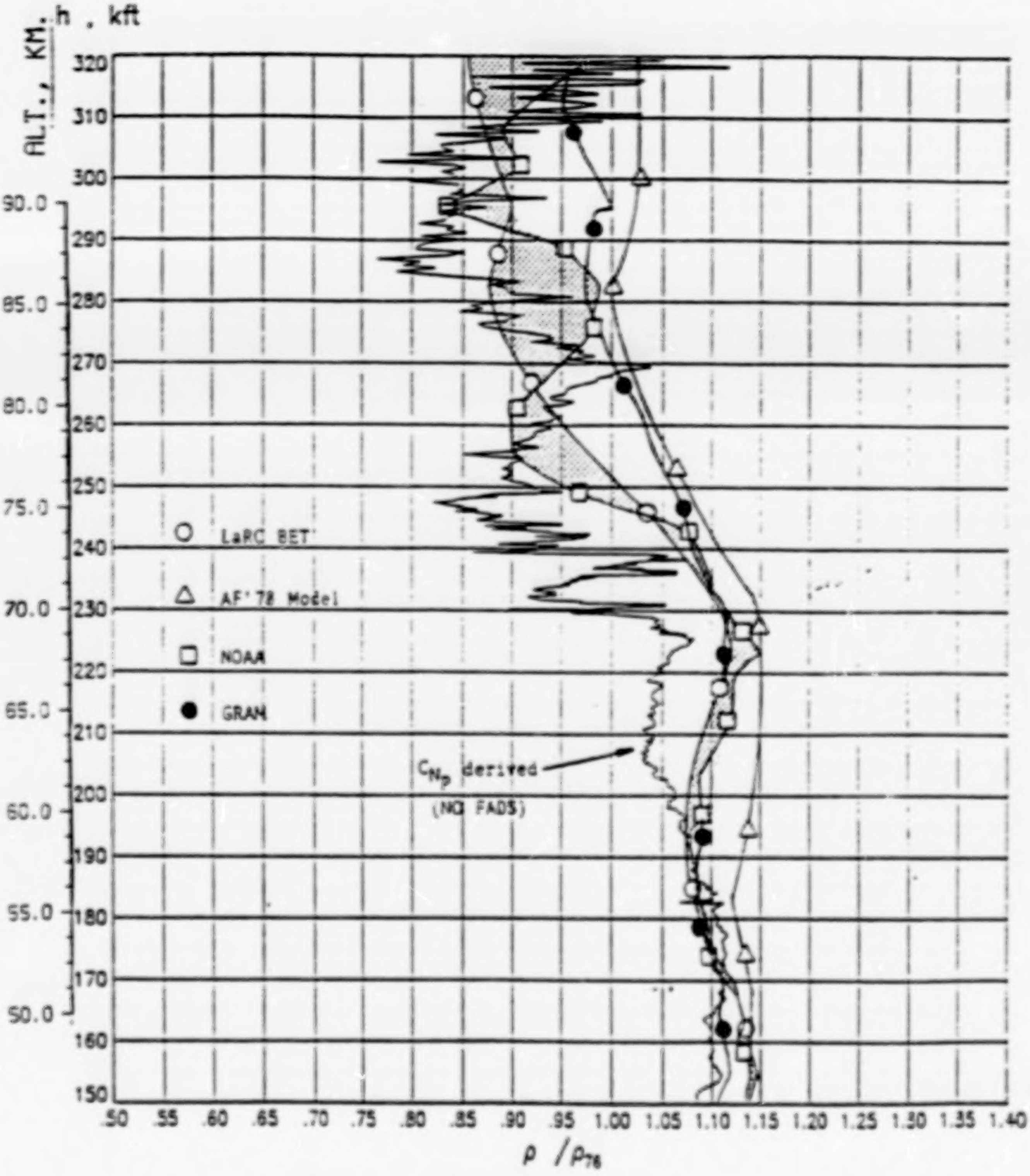
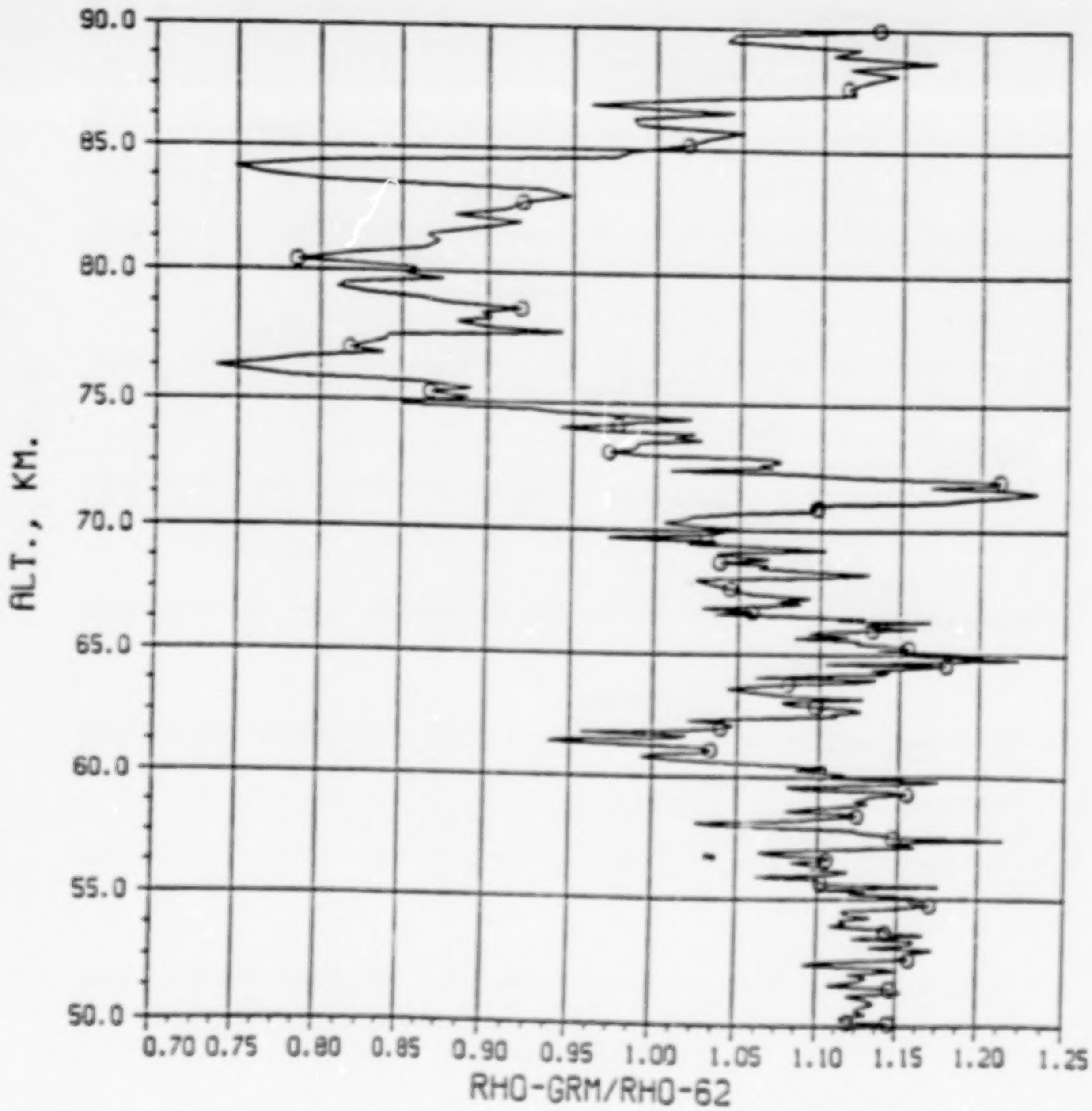


Figure A-4. STS-4 (July) density comparisons -29-

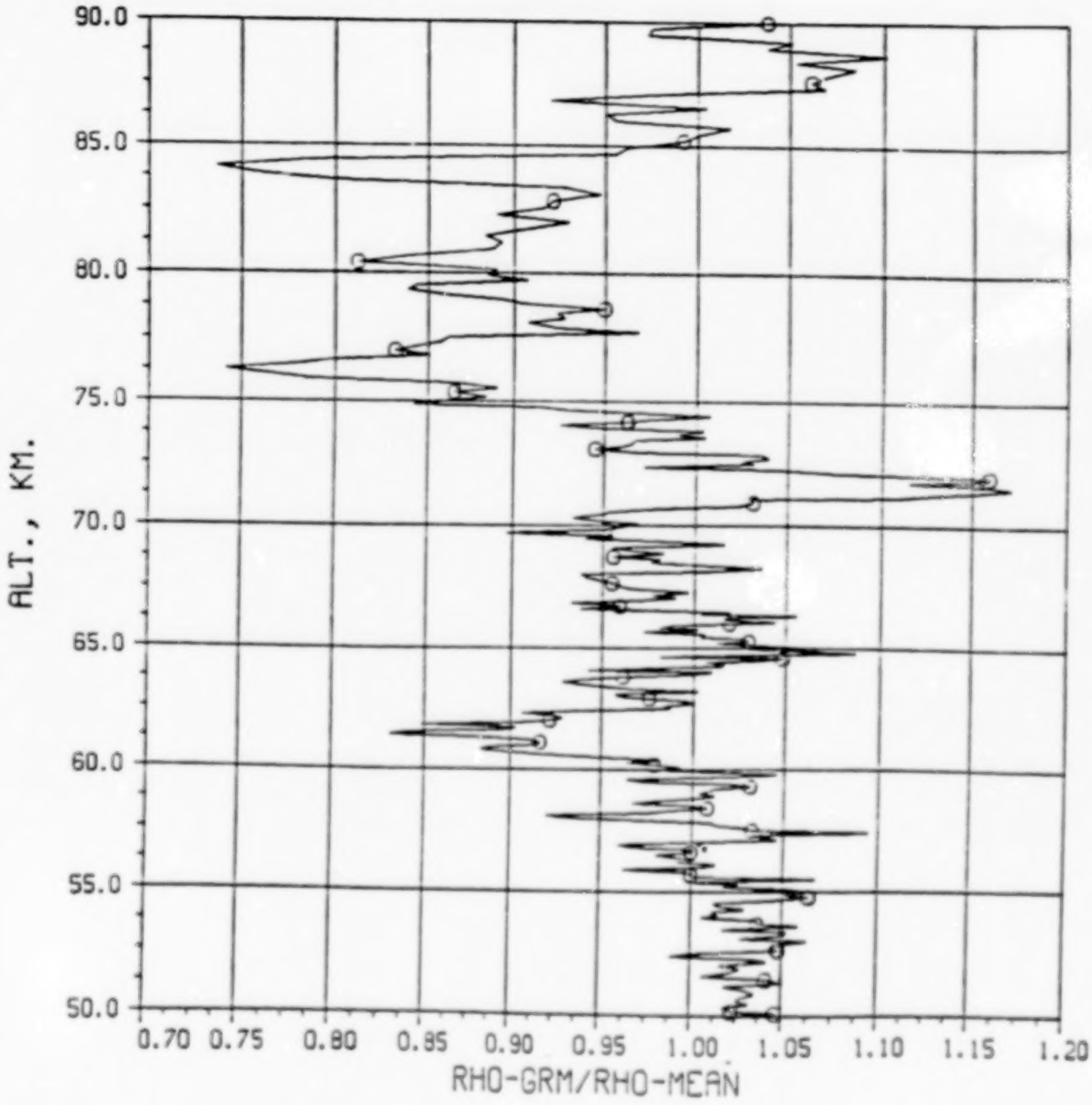
STS-4 GRAM Simulation

July- 25-30° Latitude



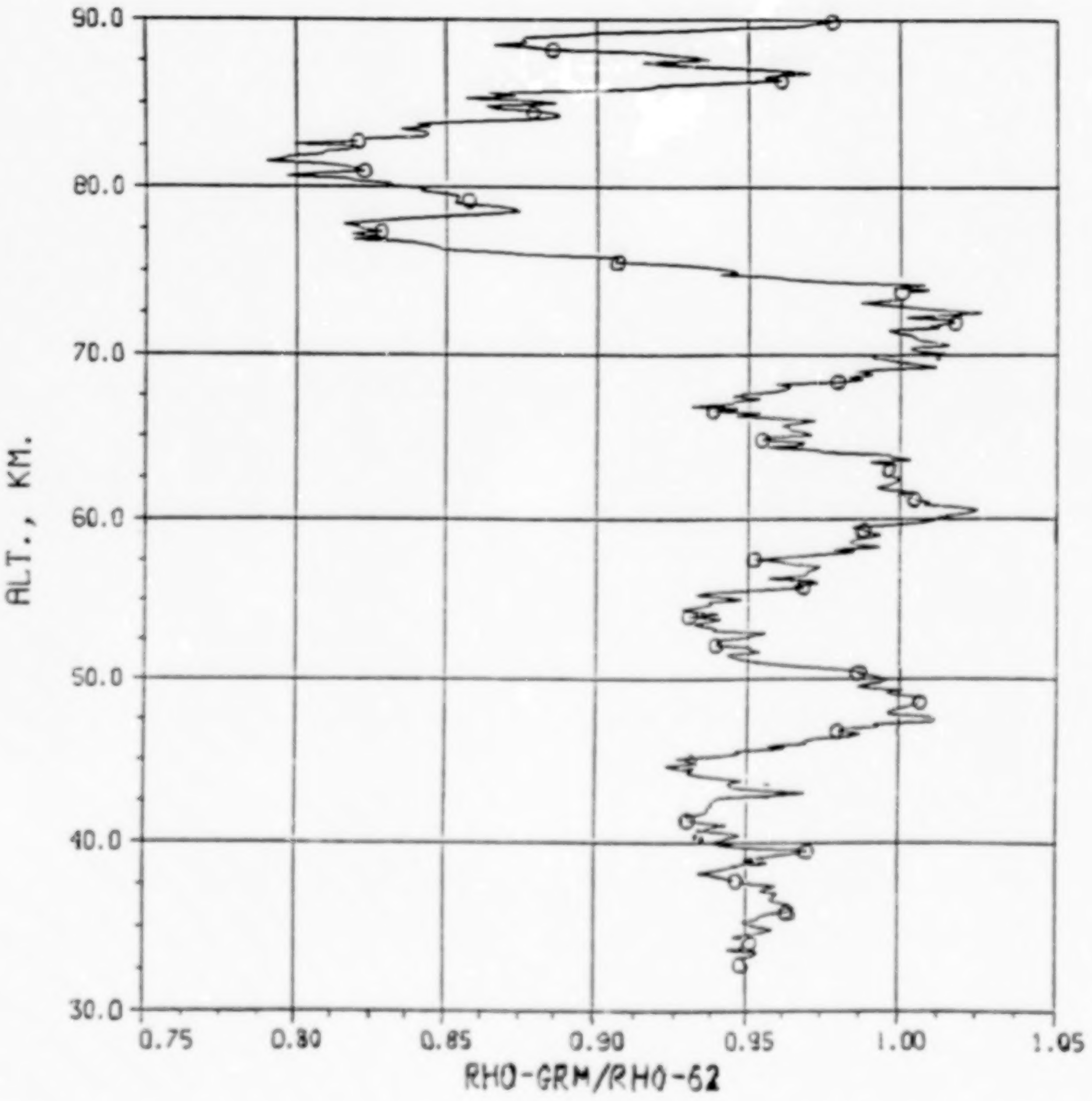
STS-4 GRAM Simulation

July - 25-30° Latitude



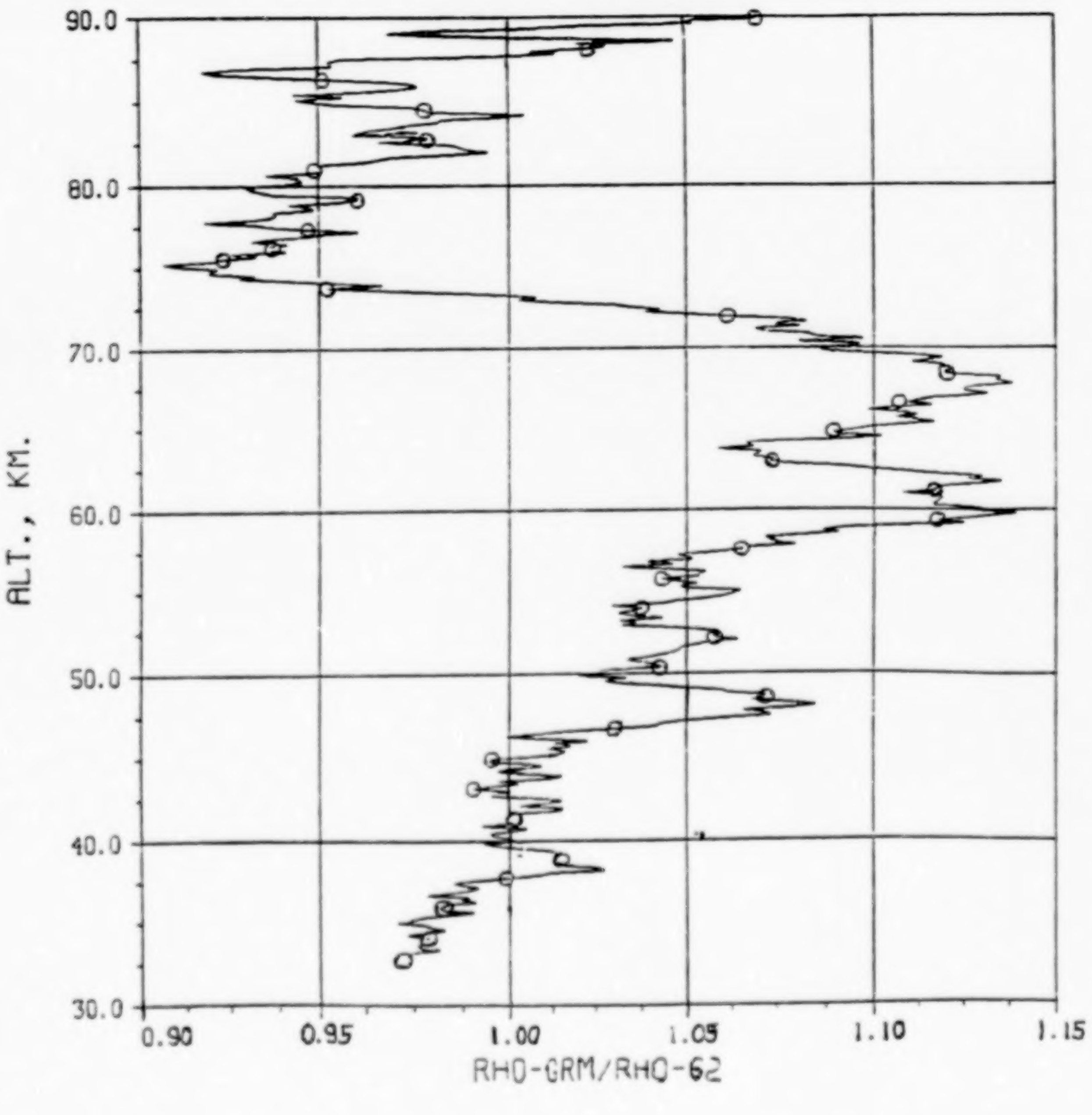
EARLY AOTV

January - 10° Latitude

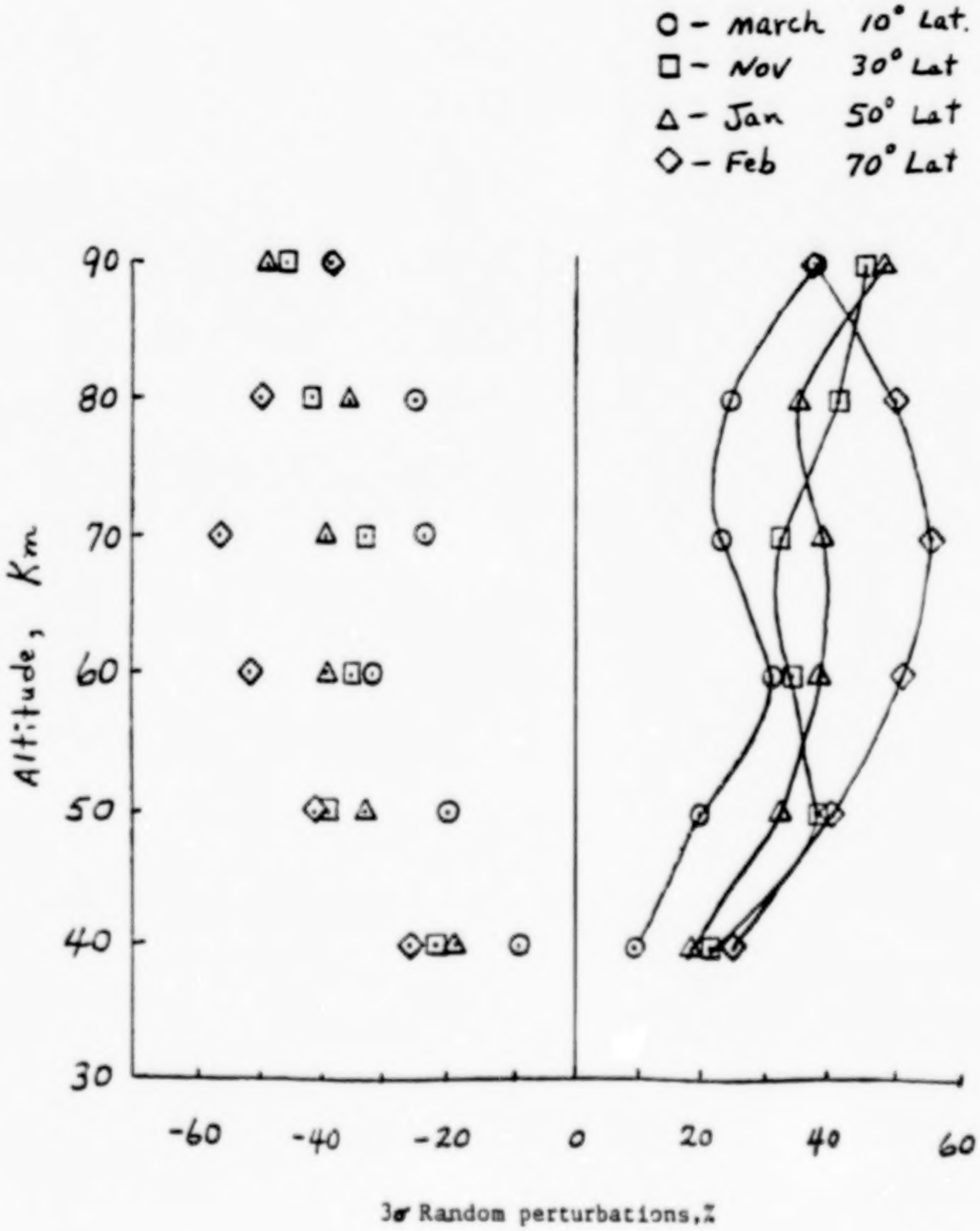


EARLY AOTV

January - 10° Latitude



GRAM RANDOM PERTURBATIONS



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UTILIZATION OF GLOBAL REFERENCE ATMOSPHERE MODEL (GRAM) FOR SHUTTLE ENTRY

Kent Joosten, NASA/Johnson Space Center

At high latitudes, dispersions in values of density for the middle atmosphere from the GRAM are observed to be large, particularly in the winter. Trajectories have been run from 28.5° to 98°. The critical part of the atmosphere for re-entry is 250,000 - 270,000 ft. 250,000 ft is the altitude where the shuttle trajectory "levels out". For "ascending" passes (entry trajectories with an ascending nodal crossing at the equator), the critical region occurs near the equator. For "descending" entries the critical region is in northern latitudes. The computed trajectory is input to the GRAM, which computes means and deviations of atmospheric parameters at each point along the trajectory. There is little latitude dispersion for the ascending passes; the strongest source of deviations is seasonal; however, very wide seasonal and latitudinal deviations are exhibited for the descending passes at all orbital inclinations. For shuttle operations the problem is control to maintain the correct entry corridor and avoid either aerodynamic "skipping" or excessive heat loads.

The high dispersions displayed in the model mean that the designers must allow for correspondingly high surface temperatures. S. Bowhill suggested that the time in the re-entry trajectory at which closed-loop control takes over might be taken as a function of season. However, designers want to be able to use a single control program sequence. At present, entry begins with open-loop control. Accuracy of the model is only a factor prior to going to closed-loop where feedback controls take over. (It is not possible to use closed-loop guidance throughout entry because of limitations on closed-loop roll control capability.)

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UTILIZATION OF GLOBAL ATMOSPHERE MODEL FOR SHUTTLE ENTRY

KENT JOOSTEN
MISSION OPERATIONS
NASA/JSC

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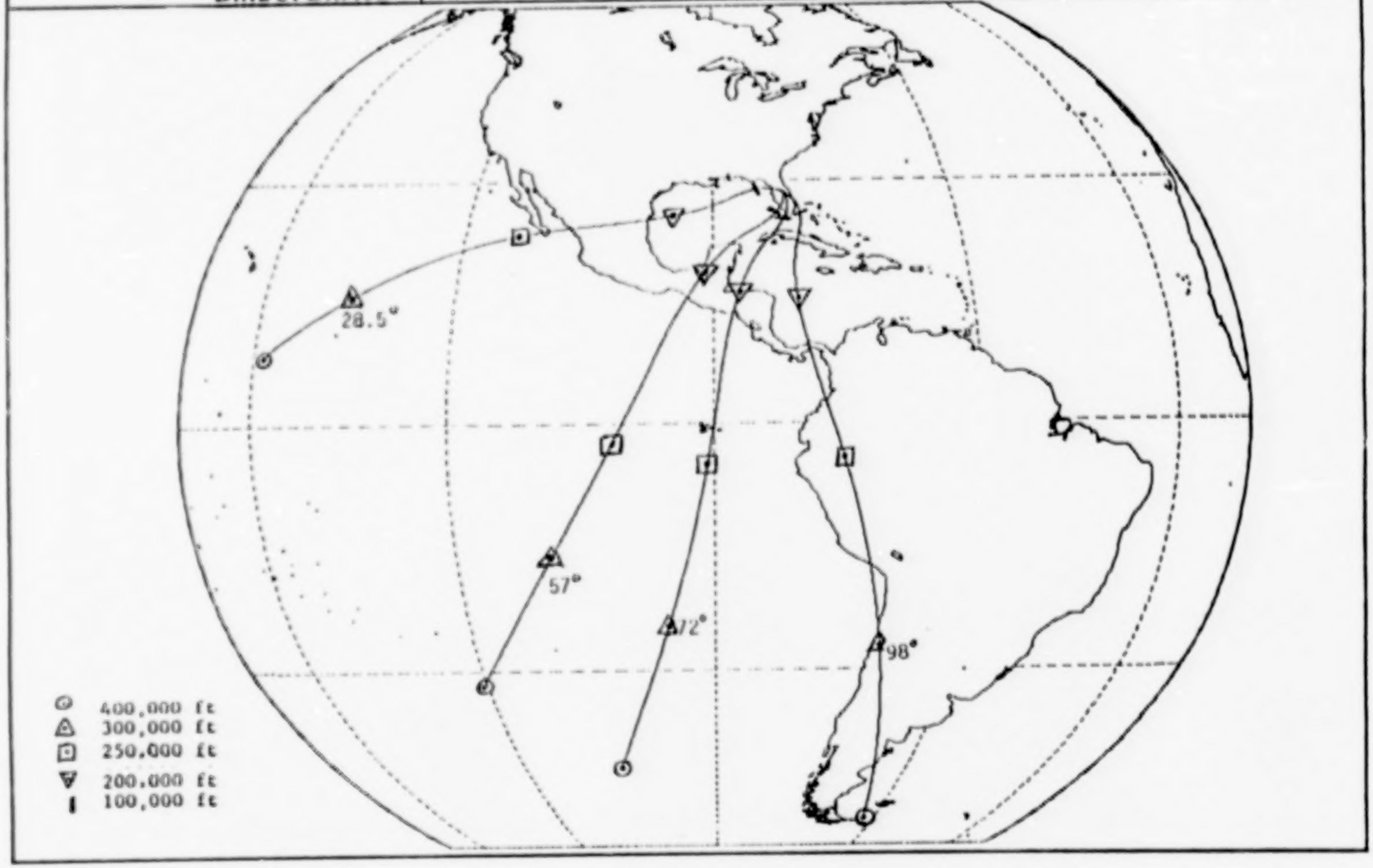
SUBJECT:
ENTRY TARGETING

NAME:
K. JOOSTEN

DATE:

- PRIMARY DRIVER IN GLOBAL MODEL WHICH AFFECTS ENTRY TARGETING IS LATITUDE
    - MODEL SHOWS SIGNIFICANT INCREASE IN DISPERSIONS AT HIGHER LATITUDES
    - MODEL SHOWS SIGNIFICANT INCREASE IN SEASONAL EFFECTS AT HIGHER LATITUDES
- ASCENDING OR DESCENDING DEORBIT PASS IS A MAJOR CONSIDERATION FOR HIGH INCLINATION MISSIONS
- ENTRY TARGETS AND DEORBIT PROP BUDGET ARE DIRECTLY INFLUENCED BY DISPERSIONS PREDICTED BY MODEL

NASA Lyndon B. Johnson Space Center *MISSION OPERATIONS DIRECTORATE*	SUBJECT: ASCENDING PASSES	NAME: K. JOOSTEN DATE:	PAGE 3


28.5°
57°
72°
98°
⊙ 400,000 ft
△ 300,000 ft
⊡ 250,000 ft
▽ 200,000 ft
I 100,000 ft

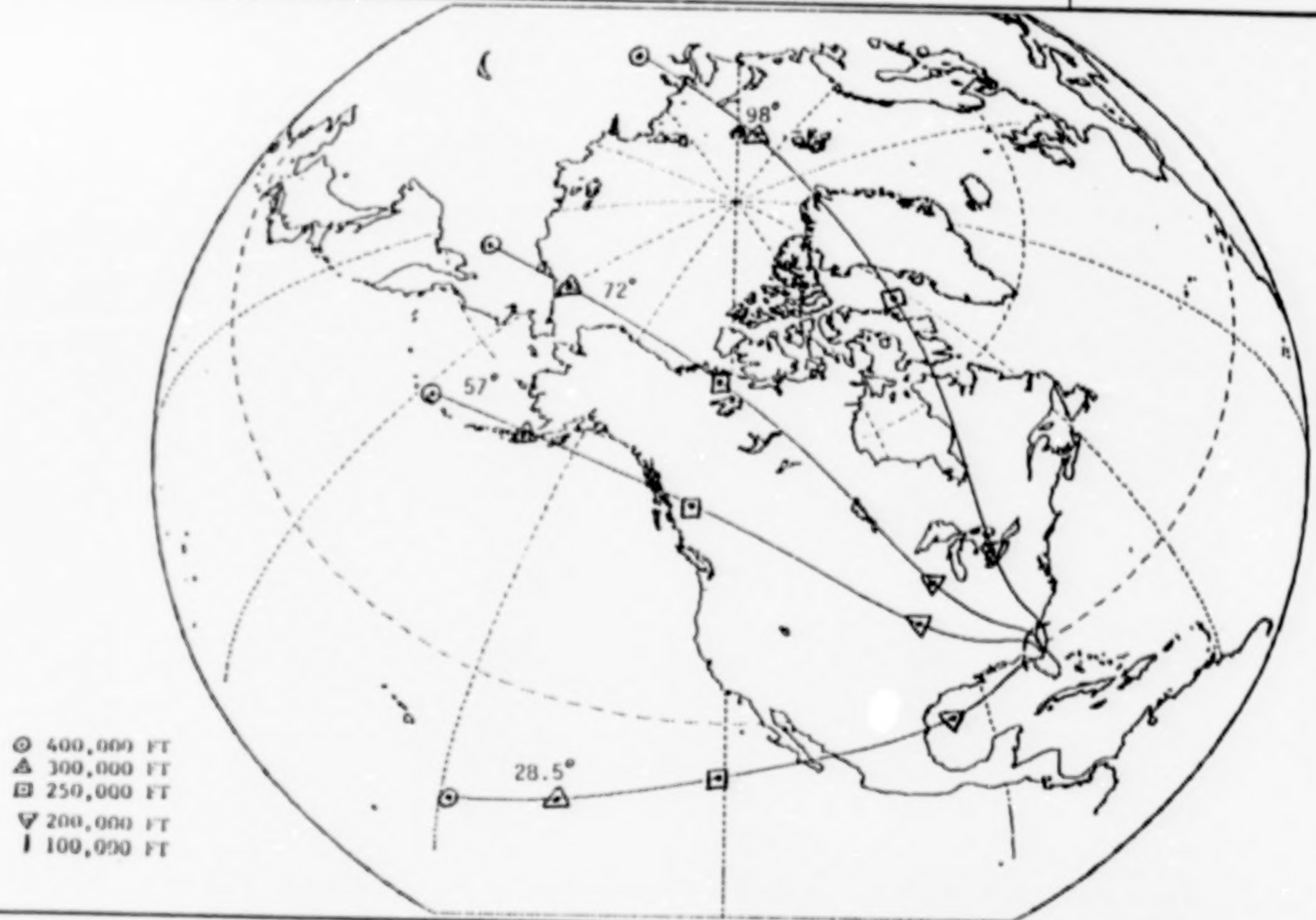
NASA
Lyndon B. Johnson Space Center
MISSION OPERATIONS DIRECTORATE

SUBJECT: DESCENDING PASSES

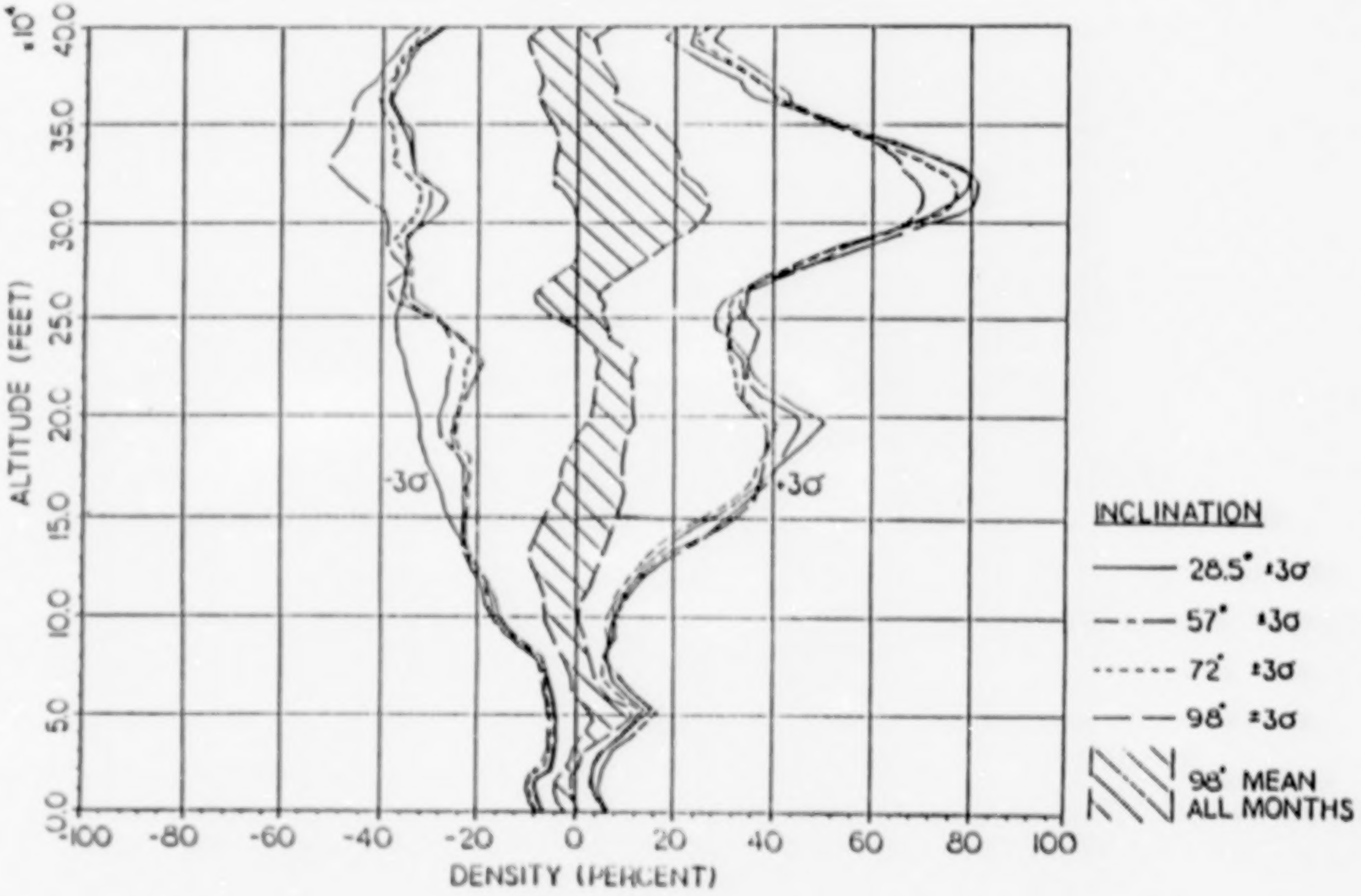
NAME: K. JOOSTEN

DATE:

PAGE 4


98°
72°
57°
28.5°
⊙ 400,000 FT
▲ 300,000 FT
⊡ 250,000 FT
▼ 200,000 FT
| 100,000 FT

NASA Lyndon B. Johnson Space Center *MISSION OPERATIONS DIRECTORATE*	SUBJECT: ASCENDING ATMOSPHERES	NAME: K. JOOSTEN
		DATE: PAGE 5



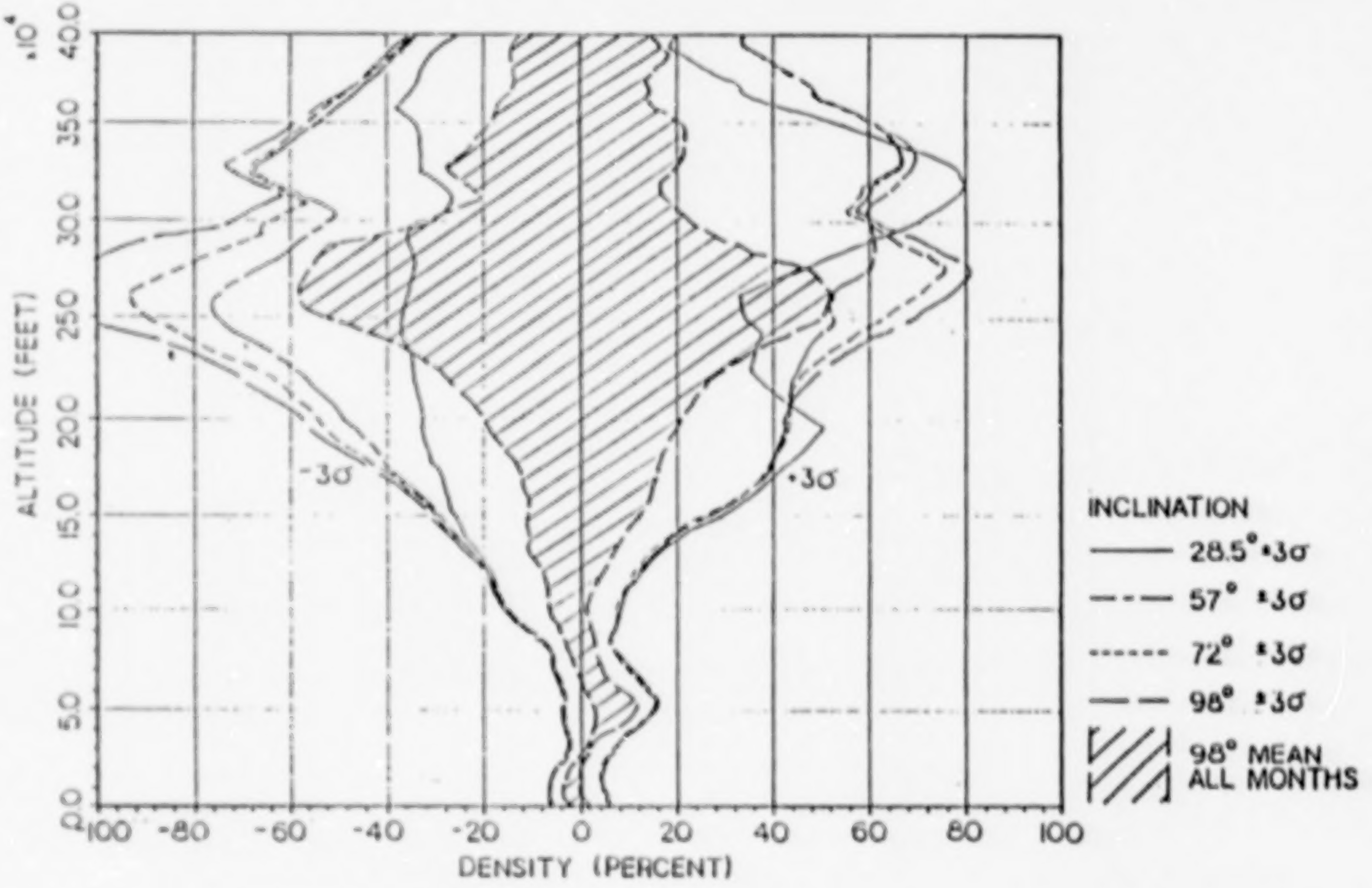
NASA
Lyndon B. Johnson Space Center
MISSION OPERATIONS DIRECTORATE

SUBJECT: DESCENDING ATMOSPHERES

NAME: K. JOOSTEN

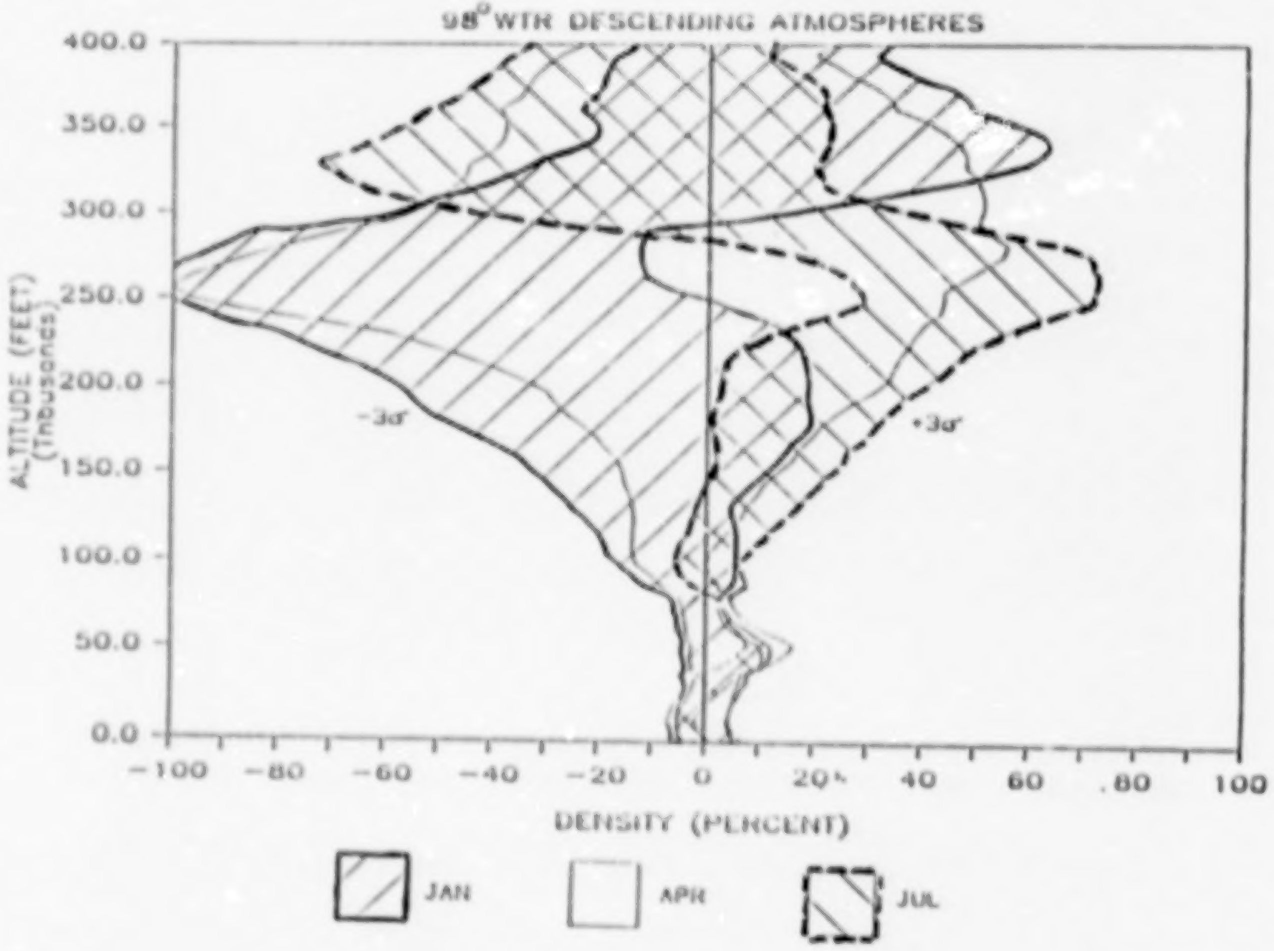
DATE:

PAGE 6



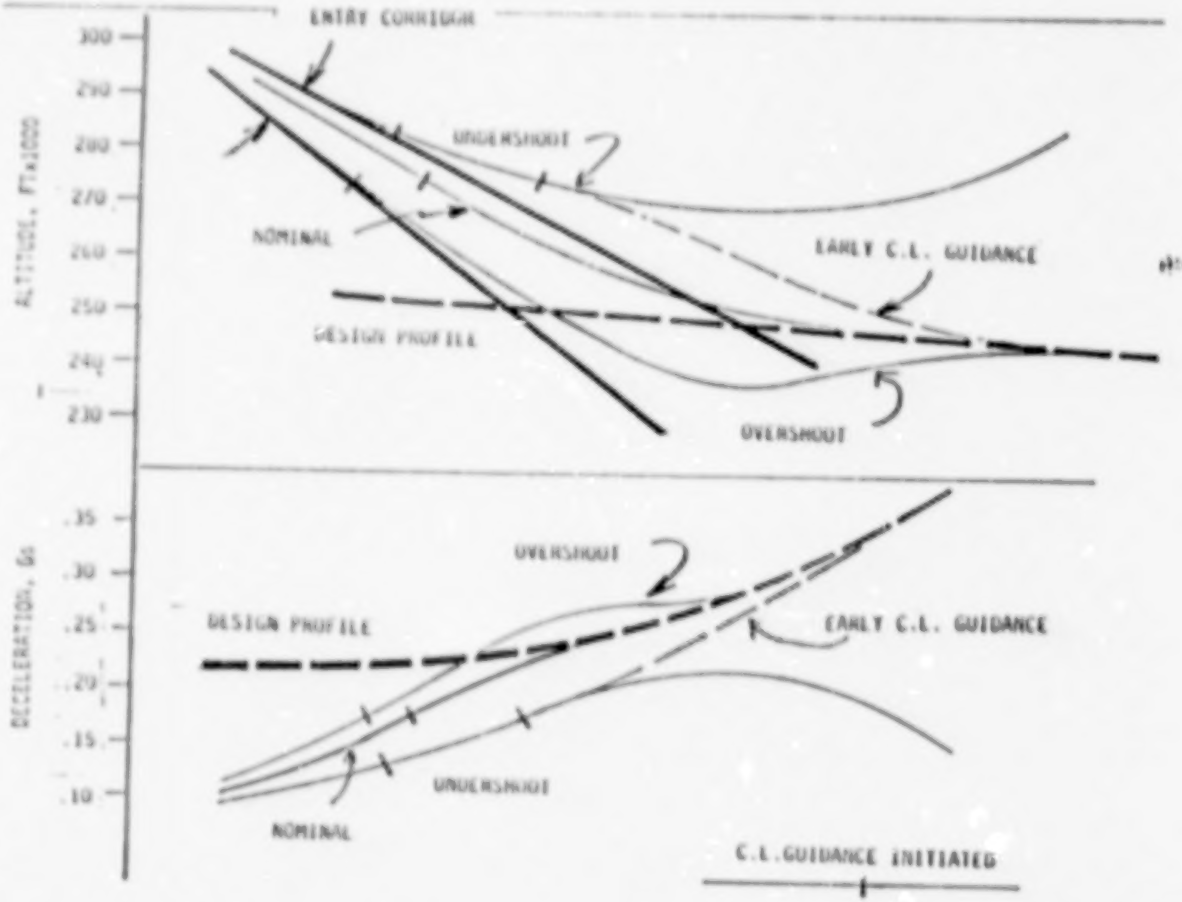
NASA Lyndon B. Johnson Space Center *MISSION OPERATIONS DIRECTORATE*	SUBJECT: SEASONAL EFFECTS	NAME: K. JOOSTEN DATE: PAGE 7

98° WTR DESCENDING ATMOSPHERES



NASA
Lyndon B. Johnson Space Center
MISSION OPERATIONS DIRECTORATE

SUBJECT:	NAME:	
SHUTTLE AEROCAPTURE	K. JOOSTEN	
	DATE:	PAGE 8



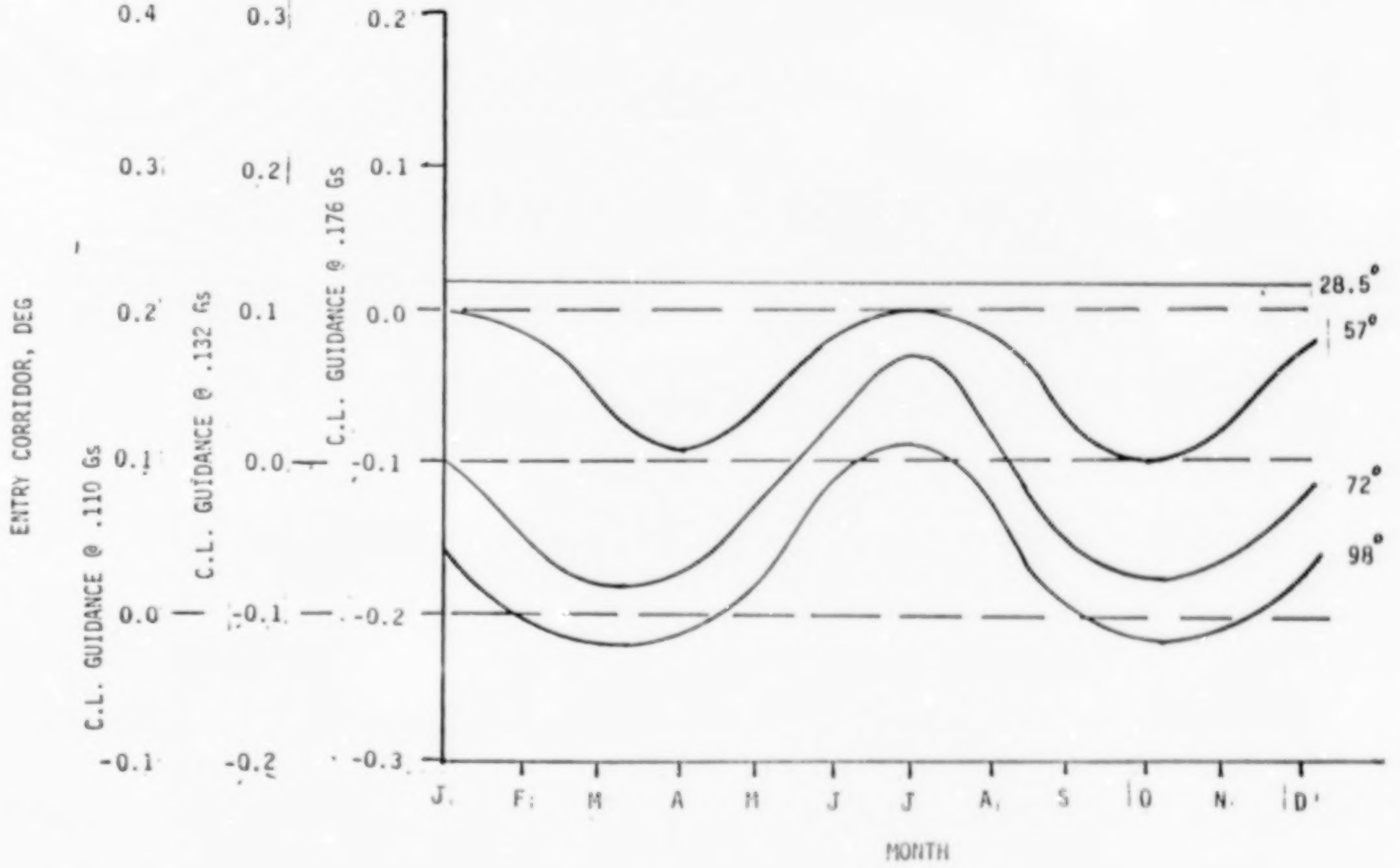
NASA
Lyndon B. Johnson Space Center
MISSION OPERATIONS DIRECTORATE

SUBJECT: ENTRY CORRIDOR MARGINS

NAME: K. JOOSTEN

DATE:

PAGE 9



SUBJECT:

THERMAL EVALUATION

NAME:
K. JOOSTEN

DATE:

- MODEL'S "DENSITY SHEARS" CAN CAUSE SURFACE TEMPERATURE TRANSIENTS
  - •• DUE TO CLOSED LOOP PITCH RESPONSE TO DRAG ERRORS
- WTR HEAT RATES AND LOADS ARE HIGH ANYWAY DUE TO HIGH RELATIVE VELOCITY AND LONG RANGE
- MONTE CARLO ANALYSIS USED TO DEFINE STEEP CORRIDOR LIMIT

NASA Lyndon B. Johnson Space Center *MISSION OPERATIONS DIRECTORATE*	SUBJECT: MONTE CARLO RESULTS: DELTA TEMPS DUE TO TRAJECTORY DISPERSIONS	NAME: K. JOOSTEN DATE: PAGE 11

SURFACE	28.5°	57° (ASC)	57° (DSC)	90° (DSC)
NOSE	81°F	79°F	173°F	172°
WING L.E.	88°	112°	216°	299°
CHINE	70°	71°	141°	180°

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USE OF THE 4D-GLOBAL REFERENCE ATMOSPHERE MODEL (GRAM) FOR SPACE SHUTTLE DESCENT DESIGN

S. M. McCarty, McDonnell-Douglas

This discussion centered on the method of using the GRAM mean and dispersed atmospheres to study skipout/overshoot requirements, to characterize mean and worst case vehicle temperatures, study control requirements, and verify design. Landing sites in these analyses range from 65°N to 30°S, while orbit inclinations vary from 20° to 98°.

McCarty's primary concern was that they cannot use as small vertical steps in the re-entry calculation as desired because the model predicts anomalously large density shear rates for very small vertical step sizes. This is an artifact of the model which needs study.

The winds predicted by the model are not satisfactory. This is probably because they are geostrophic winds and because the model has an error in the computation of winds in the equatorial regions.[Smith]

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USE OF
THE 4D-GLOBAL REFERENCE ATMOSPHERE MODEL (GRAM)
FOR SPACE SHUTTLE DESCENT DESIGN

20 NOVEMBER 1985
R. E. HITE, III
S. M. MCCARTY
(713) 280-1500

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- DESCENT USES GRAM MEAN-MONTHLY AND DISPERSED ATMOSPHERES TO:
  - DETERMINE SKIPOUT/OVERSHOOT TARGETING REQUIREMENTS
  - CHARACTERIZE MEAN AND WORST CASE VEHICLE TEMPERATURES
  - ANALYZE ALPHA MODULATION/TRAJECTORY CONTROL REQUIREMENTS
  - VERIFY DESCENT DESIGN
  - DEFINE PRODUCTS (FLIGHT DATA FILE, MCC AND ONBOARD DISPLAYS, ETC.)

- MEAN-MONTHLY AND DISPERSED ATMOSPHERE MODEL PRODUCTS CURRENTLY SUPPORT MANY SIMULATORS
  - DDS - DESIGN
  - SVDS/MONTE CARLO - PRODUCTS AND VERIFICATION
  - MCC - DEORBIT TARGETING AND REAL TIME MONITORING
  - SMS - CREW TRAINING
  - SES, SPF, SAIL SIMULATORS
  - NAV GROUP - DRAG ALTITUDE UPDATE I-LOADS

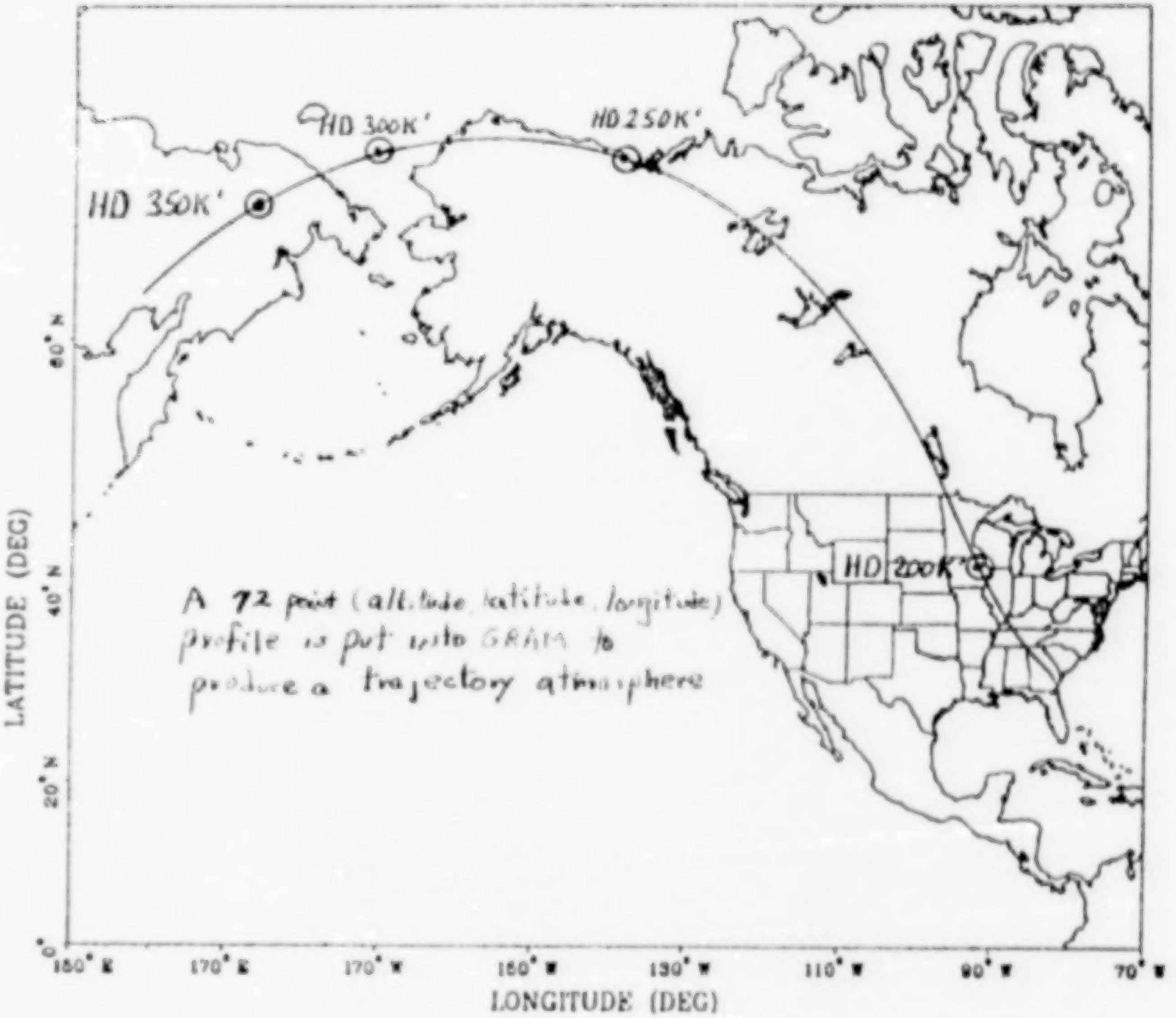
GLOBAL USE OF GRAM

- LANDING SITES, 65° N. TO 30° S. LATITUDE
- ALTITUDE, 120 TO 0 KM.
- INCLINATION 28° - 98°

CONCERNS

- SMALLER ALTITUDE SPACING SHOWS INCREASED DENSITY SHEAR RATES
- WINDS
  - DISPERSED WINDS, ALTITUDE 90 - 60 KM
  - MEAN WINDS, ALTITUDE APPROX. 20 KM
    - LARGE WIND SPIKES, 1000 FT/SEC
    - LOCATED IN THE SOUTHERN HEMISPHERE
- METHOD USED TO CALCULATE THE PERTURBATED ATMOSPHERE AND WIND STANDARD DEVIATIONS
  - BEING REVISED BY JUSTUS

KSC 70 DEG. DSC.


HD 350K'
HD 300K'
HD 250K'
HD 200K'
LATITUDE (DEG)
0°
20° N
40° N
60° N
LONGITUDE (DEG)
150° E
170° E
170° W
150° W
130° W
110° W
90° W
70° W

A 72 point (altitude, latitude, longitude) profile is put into GRAM to produce a trajectory atmosphere

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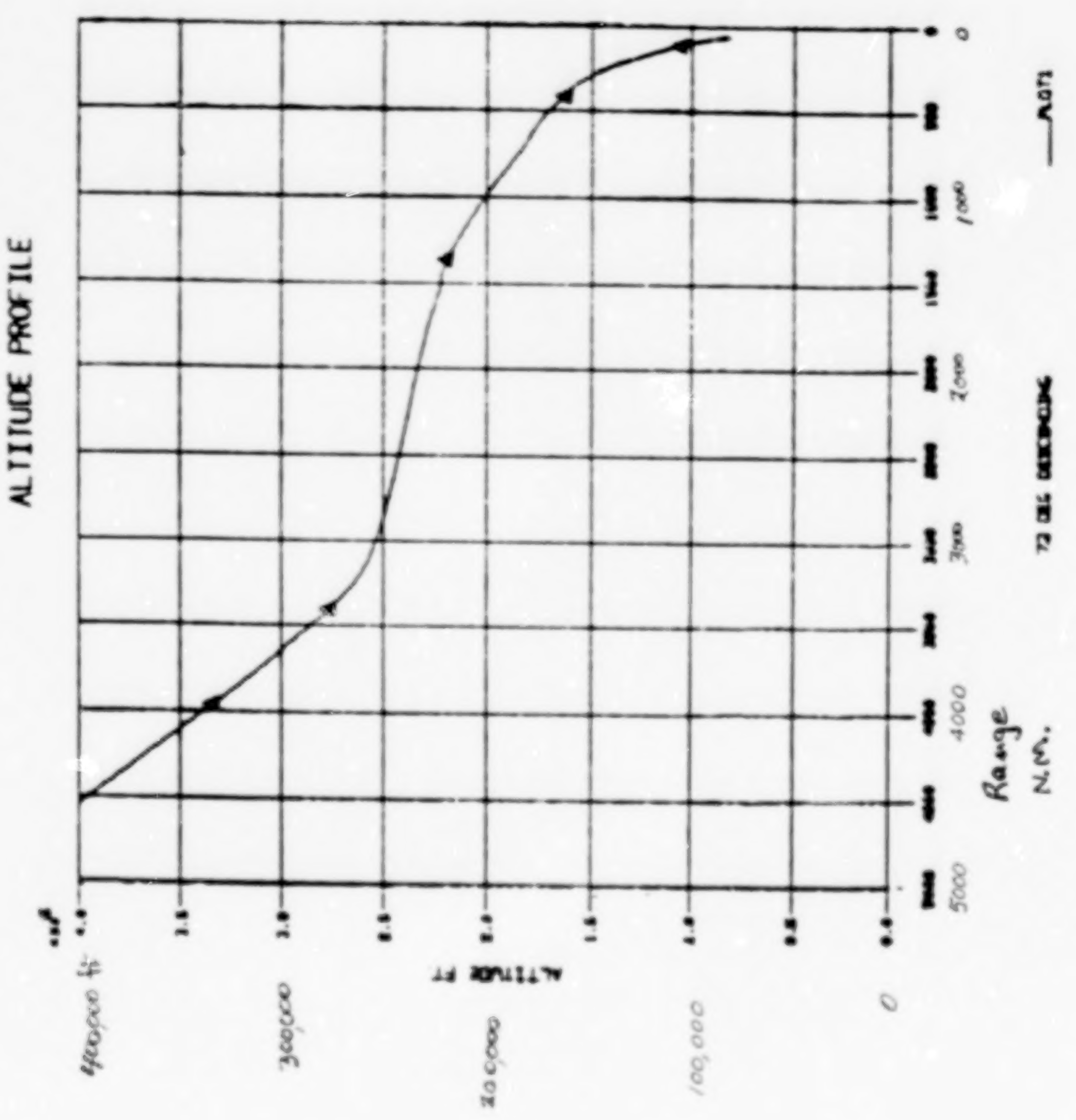

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AERO-ASSISTED ORBITAL TRANSFER VEHICLE (AOTV)

Oliver Hill, NASA/Johnson Space Center

The AOTV will make use of the atmosphere to provide braking on return from a planetary mission or geosynchronous orbit. The minimum altitude for aerobraking is typically 255,000 ft at the equator (only the equatorial region is being considered for AOTV braking). Time of the braking maneuver is typically 480 sec from 400,000 ft to 255,000 ft and back out - about 8 min. The problem is to design a control system that will be able to handle density irregularities ("bumps") such as those that have shown up in shuttle data near 280,000 ft. To obtain data, one has to use model-produced statistics or information obtained during the atmospheric transit time. The GRAM appears to bracket the shuttle data, but it is not clear that the statistics are correct. The model-data exhibits strong density shears over small step size that are probably an artifact.

[Gamble] The shuttle entry itself, particularly in the region where the trajectory is nearly horizontal, is a new data source for middle atmosphere density. There is a new National Weather Service (NWS) rocket program to study atmospheric density along shuttle entry paths (M. Gellman).

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AFE PROJECT
USE OF GRAM ATMOSPHERIC MODELS

O. HILL
NOVEMBER 19-21, 1985
MPAD-JSC

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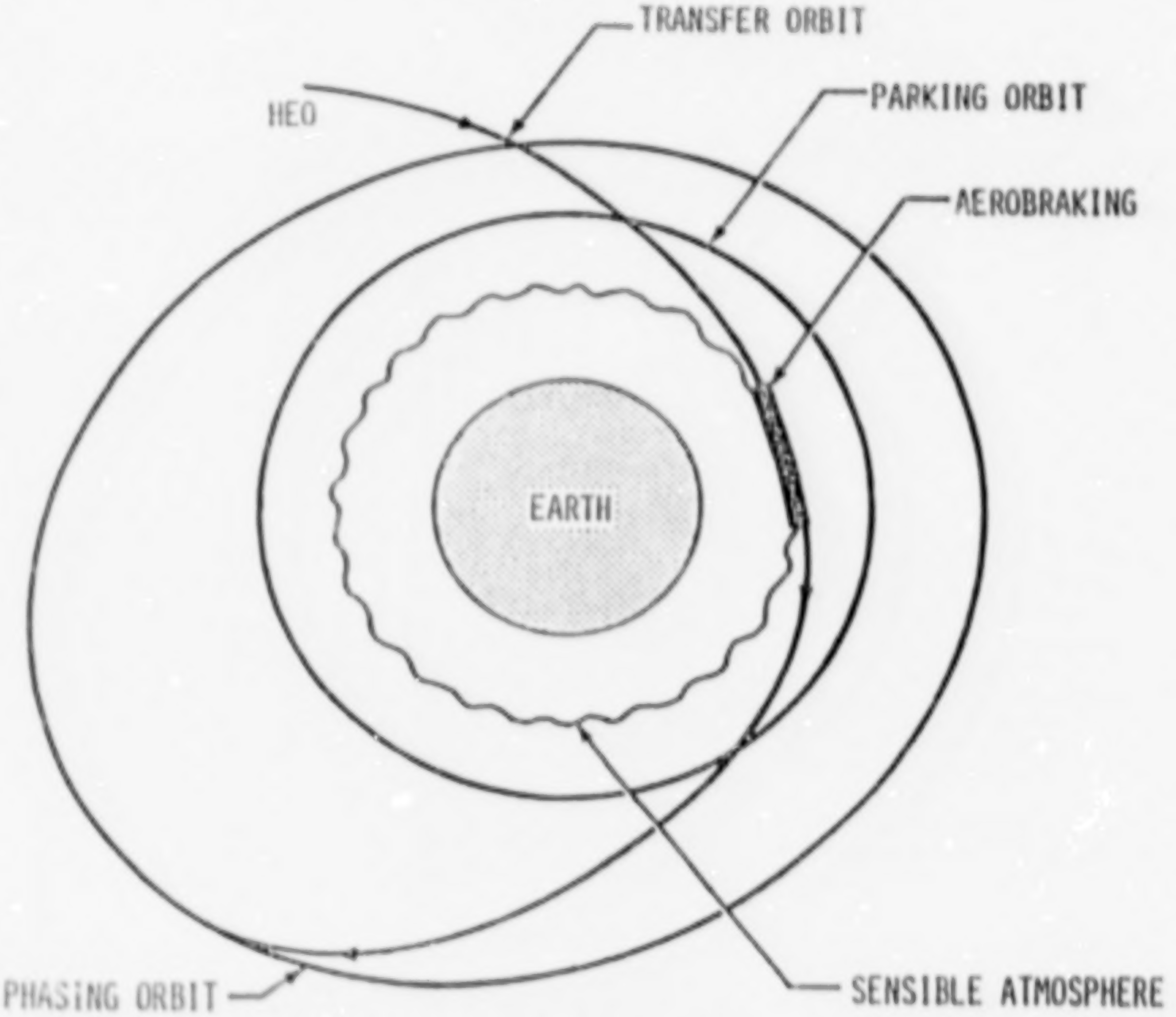
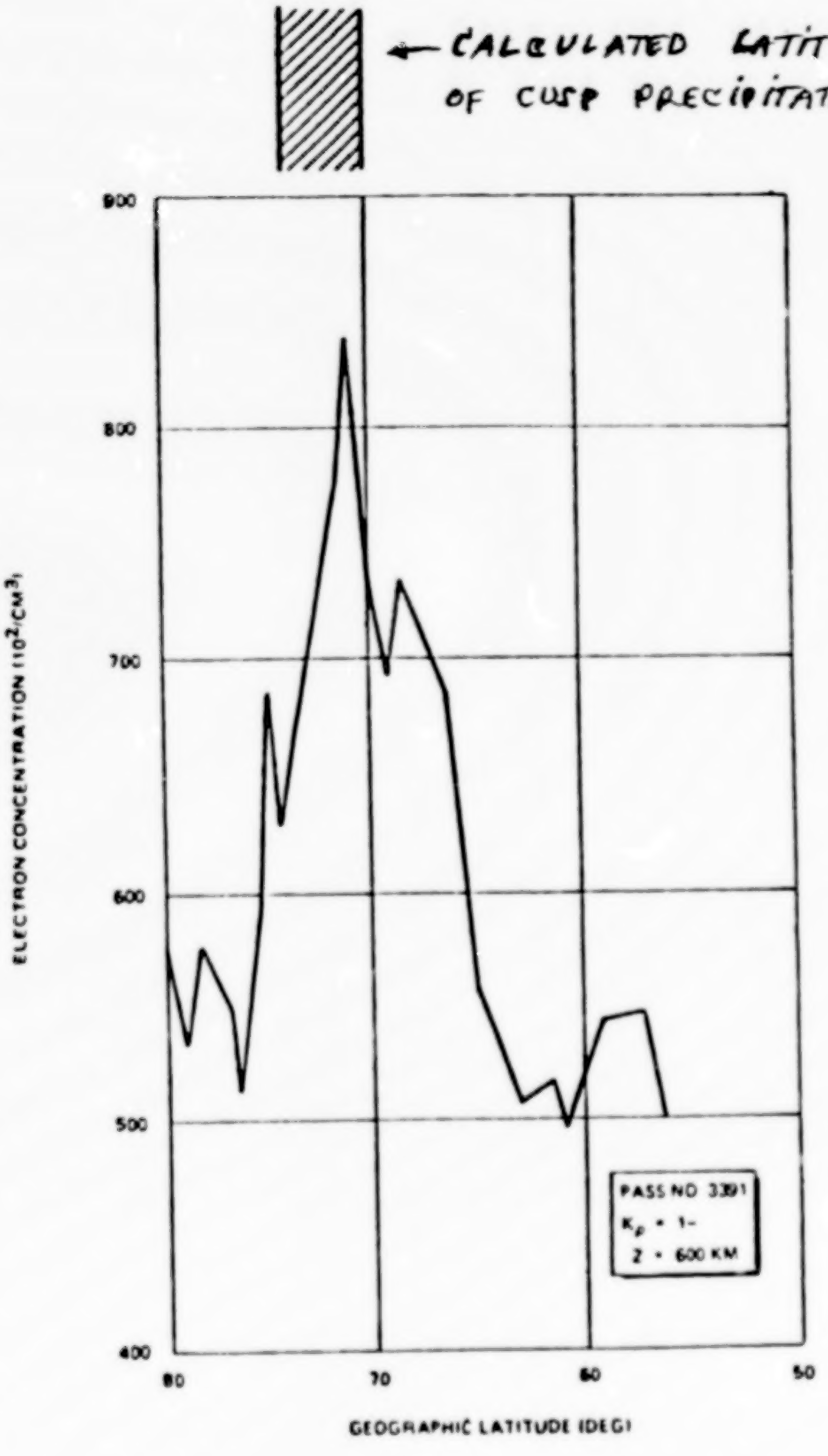
GUIDANCE OBJECTIVE

CENTRAL ANGLE
OF 37 DEG

TOTAL FLIGHT TIME
OF 480 SEC

MINIMUM ALTITUDE
OF 255000 FT


TRANSFER ORBIT
HEO
PARKING ORBIT
AEROBRAKING
EARTH
PHASING ORBIT
SENSIBLE ATMOSPHERE



← CALCULATED LATITUDES OF CUSP PRECIPITATION

FIGURE 8. ELECTRON CONCENTRATIONS MEASURED BY ALOUETTE I ON JUNE 4, 1963.

C-24

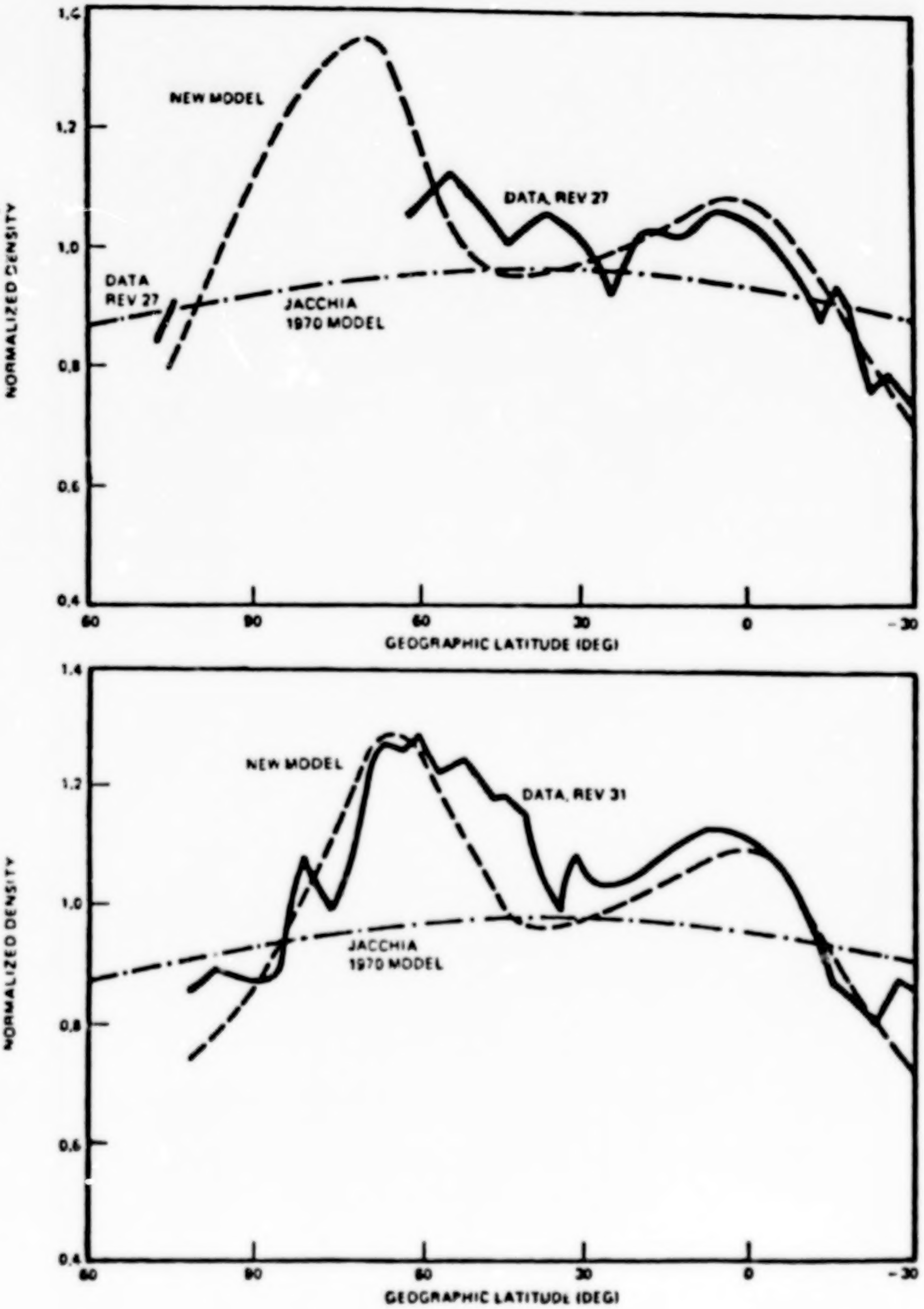


FIGURE 9. LOGACS DATA COMPARED WITH ATMOSPHERIC MODELS

FIG. 10. EFFECT OF DAYSIDE CUSP HEATING ON DENSITIES NEAR 400 KM

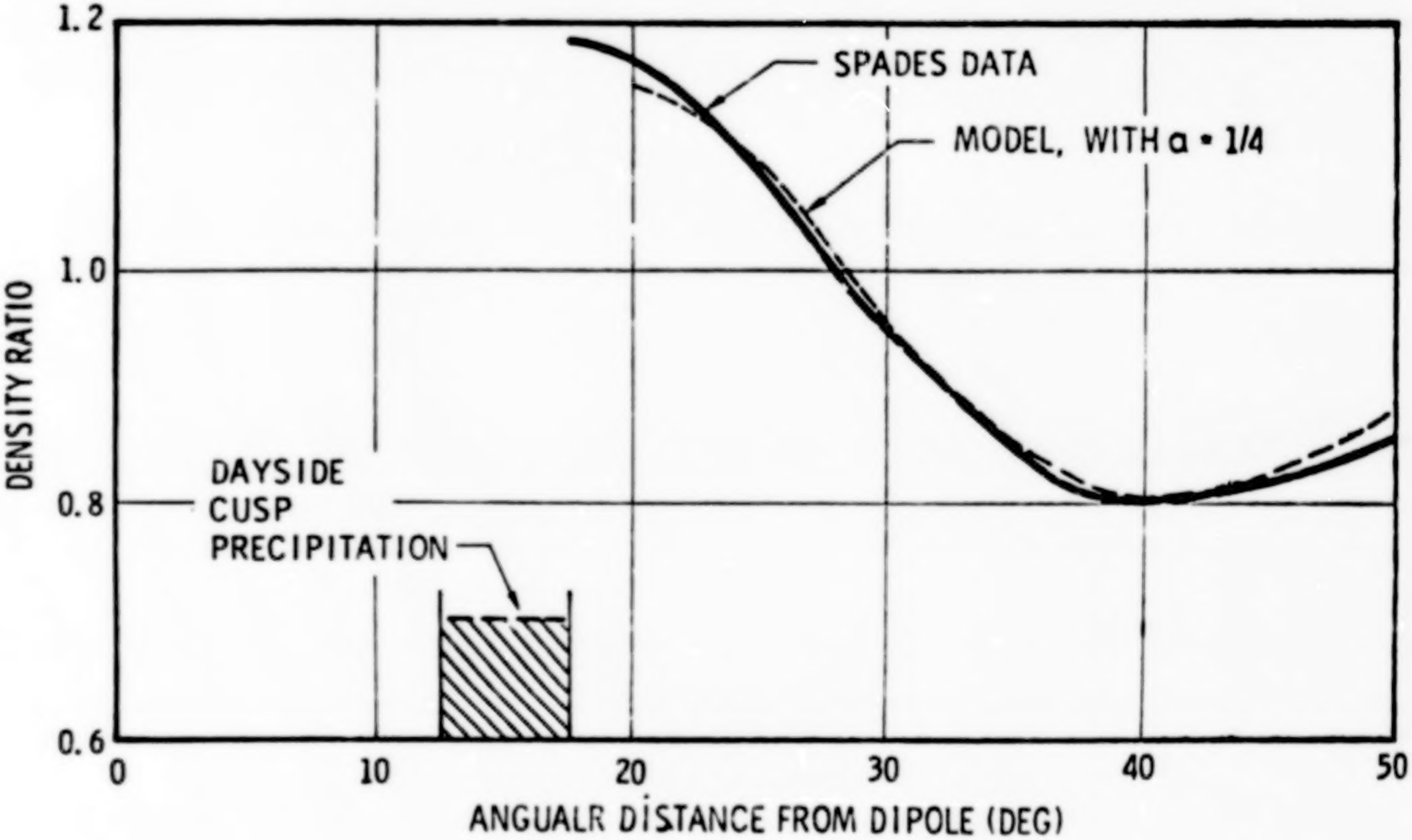
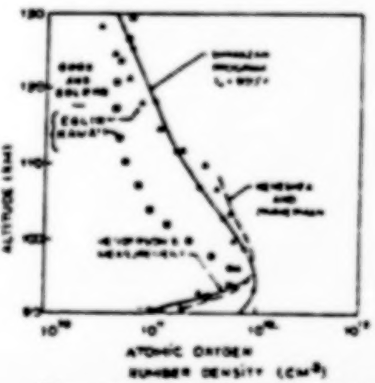
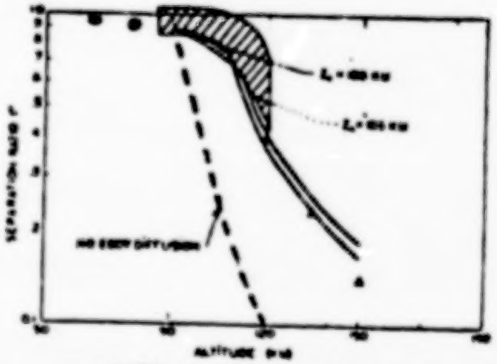


Fig. 11 DEPENDENCE OF COMPOSITION ON EDDY DIFFUSION



Measurements and models of the concentration of atomic oxygen. All the measurements agree in showing a rapid decrease below 95 km. Shimasaki's calculated curve assumed that the eddy diffusion coefficient D_e was 1×10^7 cm² sec⁻¹ above 105 km and fell linearly to 2×10^6 at 90 km. In Keneshea and Zimmerman's calculation, D_e reached its maximum value of 1×10^7 at 80 km. The comparison between theory and experiment shows that D_e is large below 100 km.



Ar/N_2 separation ratios. In the two theoretical curves (heavy lines), which were computed by a modification of the *Shimasaki* [1967] program, the eddy diffusion coefficient is assumed to reach its maximum value (2×10^7 cm²/sec) at Z_0 and to decrease rapidly above and below this altitude. The theoretical calculations succeed in reproducing the curvature seen in the experimental data, but the data represented by the circles and triangles would be better fitted if Z_0 were below 100 km. The measurement of Philbrick et al. (shaded area) indicates that mixing extended to a higher altitude than in the other measurements. This may be because turbulence. extended to 112 km during their flight.

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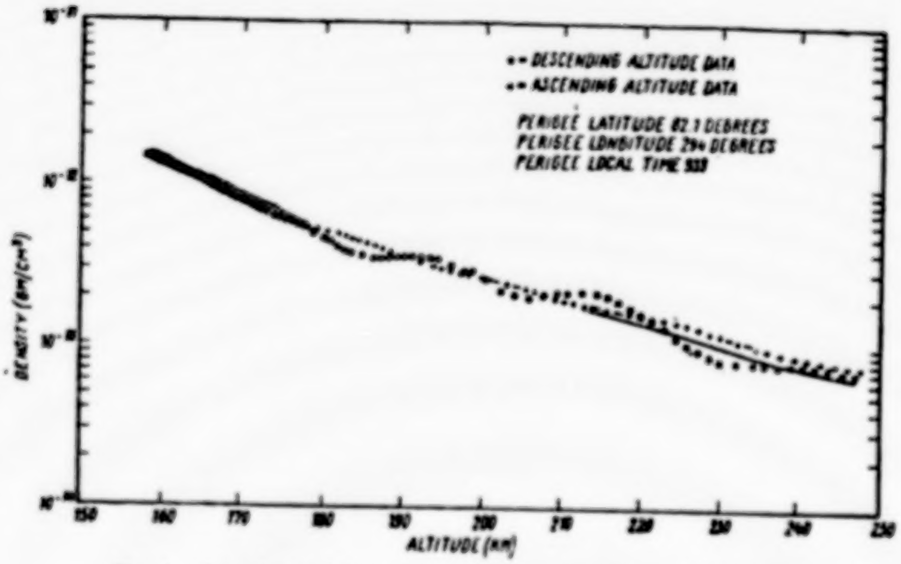
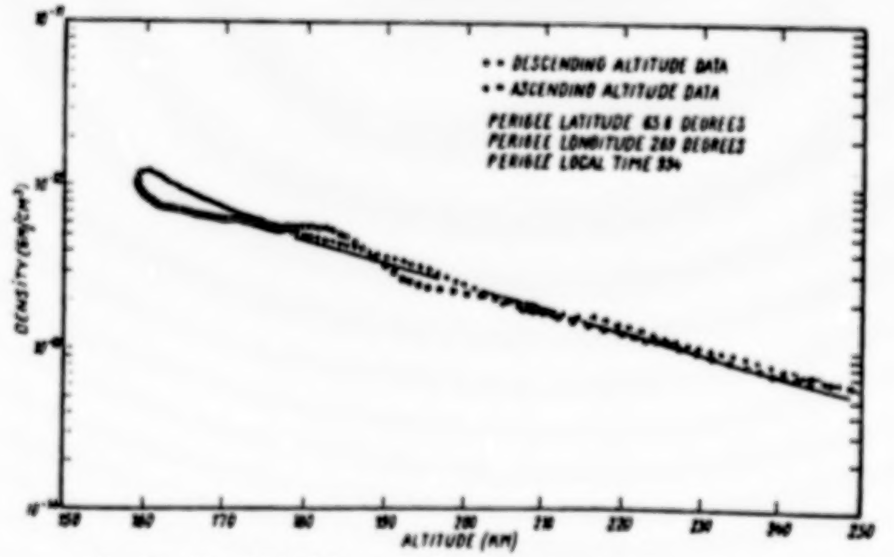
Space Research XII – Akademie-Verlag, Berlin 1972

FIG. 12. GRAVITY WAVES OBSERVED IN HIGH LATITUDE NEUTRAL DENSITY PROFILES

F. A. Marcos and K. S. W. Champion



Density data obtained from accelerometer on satellite OV1-15 for orbit 358 on 6 August 1968 showing wave-like disturbance.



Density data obtained from accelerometer on satellite OV1-15 for orbit 373 on 7 August 1968 showing wave-like disturbance.

ADDENDA

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ACRONYMS/SYMBOLS

A	Area
AFE	Aeroassist Flight Experiment
AFGL	Air Force Geophysics Laboratory
AOTV	Aero-assisted Orbital Transfer Vehicle
Ap,aa,Kp,AE	Measures of disturbance of the Earth's magnetic field
C_d	Drag coefficient
CG	Center of gravity
CMG	Control Moment Gyro
CP	Center of pressure
$F_{10.7}$	Solar radio noise flux at 10.7 cm wavelength
GRAM	Global Reference Atmosphere Model
GSFC	Goddard Space Flight Center
IOC	Initial Operational Capability
JSC	Johnson Space Center
LaRC	Langley Research Center
m	Mass
MAP	Middle Atmosphere Program
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
Nms	Newton-meter-second
NOAA	National Oceanic and Atmospheric Administration
PCS	Pointing Control System
RWA	Reaction Wheel Assembly
ST	Space Telescope
STEA	Short Term Extreme Atmosphere density

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LIST OF ATTENDEES

NASA - USRA
WORKSHOP ON UPPER AND MIDDLE ATMOSPHERIC DENSITY MODELING REQUIREMENTS FOR SPACECRAFT DESIGN AND OPERATIONS
November, 1985, Huntsville Alabama

Arthur Belmont
Control Data Corp.
Code HQM-251
2800 E. Old Shakespeare Road
Minneapolis, MN 55440
(612) 853-8100 x3595

Maureen Barrett
Rockwell
Satellite Systems Division
M.S. AD 35
2214 Lakewood Blvd.
Downey, CA 90214
(213) 922-2464

R.C. Blanchard
NASA/Langley Research Center
MS 366
Hampton, VA 23655
(804) 865-3031

Sidney Bowhill
University of Illinois
Dept. of Electrical & Computer Engineering
1405 West Green Street
Urbana, IL 61801
(217) 333-4150

Jerre Bradt
Boeing Aerospace Corp.
M.S. 8-C-47
P.O. Box 3999
Seattle, WA 98124
(206) 773-2192

Violis Buckelew
NASA/Marshall Space Flight Center
Code EL 23
Huntsville, AL 35812
(205) 453-1089

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Charles Campbell
Lockheed
2400 NASA Road 1
Mail Code B12
Houston, TX 77258
(713) 333-6107

George Carignan
University of Michigan
2455 Hayward
Ann Arbor, MI 48109
(313) 764-9462

K.W. Champion
AFGL
Hanscom Air Force Base
Bedford, Ma 01731
(617) 861-3033

George Chimones
Georgia Institute of
Technology
School of Geophysical Sciences
225 North Avenue, N.W.
Atlanta, GA 30322
(404) 894-3893

Michael J. Crawford
Navy Astronautics Group
SPM 3321
Point Mugu, CA 93042-5013
(805) 989-8702

Derek Cunnold
Georgia Institute of
Technology
Atlanta, GA 30332
(404) 894-3814

Michael Davis
North Georgia College
Dept. of Physics
Dahlonega, GA 30597
(404) 864-3391

Vincent Dauro
NASA/Marshall Space Flight
Center
Mail Code PD 34
Huntsville, AL 35812
(205) 453-3936

M. H. Davis
USRA
P.O. Box 391
Boulder, CO 80306
(303) 449-3414

Harold Euler
NASA/Marshall Space Flight
Center
Code EL 25
Huntsville, AL 35812
(205) 453-1092

John Findlay
Flight Mechanics & Control
47 East Owens Way
Hampton, VA 23669
(804) 722-7545

James C. Fox
KMS Fusion
3621 S. State Street
Ann Arbor, MI 48106
(313) 769-8500

David Fritts
University of Alaska
Room 506 F, Elvey Bldg
Fairbanks, Alaska 99775-1300
(907) 474-7845

Joe D. Gamble
NASA/Johnson Space Center
ET3 Bldg 32, Room 203
Houston, TX 77058
(713) 483-5071

Alan Hedin
NASA/Goddard Space Flight
Center
Code 614.0
Greenbelt, MD 20771
(301) 344-8393

Oliver Hill
NASA/Johnson Space Center
FM 5 Bldg. 30, Room 2049
Houston, TX. 77058
(713) 483-3458

Ed Hite
McDonnell Douglas Corp.
16055 Space Center Blvd.
Mail Code T6D
Houston, TX 77062
(713) 280-1680

Mariam Hopkins
NASA/Marshall Space Flight
Center
ED 15
Huntsville, AL 35812
(205) 453-4587

R. J. Hung
University of Alabama
4701 University Drive, NW
Hunstville, AL 35812
(205) 895-6077

Bill Jeffries
Computer Sciences Corp.
4912 Research Drive
Huntsville, AL 35805
(205) 837-9060

B. Kent Joosten
NASA/Johnson Space Center
DM 5
Houston, TX 77058
(713) 483-4418

JoAnn Joselyn
NOAA
325 Broadway
Boulder, CO 80303
(303) 497-5147

Dale L. Johnson
NASA/Marshall Space Flight Center
ED 44
Huntsville, AL 35812
(205) 453-3101

C. G. Justus
Georgia Institute of
Technology
School of Geophysical Sciences
Atlanta, GA 30332
(404) 894-3890

David Kayser
Aerospace Corp.
Bldg. A6, Mail Stop 2407
PO Box 92957
Los Angeles, CA 90009
(213) 648-7016

John Kaveney
Rockwell International Corp.
Downey, CA 90241
(805) 498-4545

Brian Kennedy
University of Michigan
Space Research Physics Lab
2455 Hayward
Ann Arbor, MI 48109
(313) 764-6561

Timothy Killeen
University of Michigan
2455 Hayward
Ann Arbor, MI 48109
(313) 763-6218

Joseph Liu
AF/Space Command
Space Command/DOA
Colorado 80914
(303) 554-5467

Frank Marcos
AFGL
Hanscom Air Force Base
Bedford, MA 01731
(617) 861-3037

Cliff Matsumoto
Air Weather Service
HQ-AWS/DNXA
Scott Air Force Base
Illinois 62225-5008
(618) 256-4731

James McCarter
NASA/Marshall Space Flight
  Center
PD 32
Huntsville, AL 35812
(205) 453-1092

Steve McCarty
McDonnell Douglas Corp.
16055 Space Center Blvd.
Mail Code T6E
Houston, TX 77062
(713) 280-1500

Robert McClatchey
AFGL
Hanscom Air Force Base
Bedford, MA 01731
(617) 861-2975

Gene McSwain
NASA/Johnson Space Center
EH 22
Houston, TX 77058
(713) 483-4477

Kenneth Moe
1520 Sandcastle Drive
Corona Del Mar, CA 92625
(714) 644-1605

John Nicholson
Langley Research Center
Hampton, VA 23665
(804) 865-2000

Gerald Nurre
NASA/Marshall Space Flight
  Center
ED 12
Huntsville, AL 35812
(205) 453-4580

Douglas ReVelle
N. Illinois University
Room 118 Davis Hall
Meteorology Program
Dekalb, IL 60115
(815) 753-0631

Raymond G. Roble
NCAR
Box 3000
Boulder, CO 80307
(303) 494-5151 x660

Robert Roper
Georgia Institute of
  Technology
School of Geophysical Sciences
Atlanta, GA 30332
(404) 894-3892

F. Rich
AFGL
Hanscom Air Force Base
Bedford, MA 01731
(617) 861-2431

H. H. Sargent, III
NOAA
SEL/SESC R432
Boulder, CO 80303
(303) 497-3697

Francis Schmidlin
NASA/GSFC
Bldg. #106
Wallops Island, VA 23337
(804) 824-3411

Chalmers Sechrist
University of Illinois
Dept. of Electrical & Computer
  Engineering
1406 W. Green Street
Urbana, IL 61801
(217) 333-2302

Jack Slowey
SAO
Center for Astrophysics
60 Garden Street
Cambridge, MA 02138
(617) 495-7214

O. E. Smith
Computer Systems Corp.
4912 Research Drive
Huntsville, AL 35805
(205) 837-9060 x346

Robert E. Smith
USRA
139 McMurtrie Drive
Huntsville, AL 335806
(205) 895-0582

Steve A. Smith
Code ED44
NASA Marshall Space Flight
  Center
Huntsville, AL 35812
(205) 544-1658

Michael Susko
NASA/Marshall Space Flight
  Center
ED 44
Huntsville, AL 35812
(205) 453-3101

Gary Swenson
Lockheed Missile & Space Corp.
Bldg. 255, Org. 9120
3170 Porter Drive
Palo Alto, CA 94304-1211
(415) 858-4097

Joe M. Straus
Aerospace Corporation
MS M2-255
P O Box 92957
Los Angeles, CA 90009
(415) 424-3297

Walter Unterberg
Rockwell International Corp.
Rocketdyne Division
Dept. 631, FB 25
6633 Canoga Avenue
Canoga Park, CA 91303
(818) 700-3627

William W. Vaughan
Research Institute
University of Alabama
Huntsville, AL 35899
(205) 895-6479

August C. Weisler, Jr.
NASA/Marshall Space Flight
  Center
ED 13
Huntsville, AL 35812
(205) 453-4715

Gerald Wittenstein
NASA/Marshall Space Flight
  Center
EL 25
Huntsville, AL 35812
(205) 453-1093

Samuel Zimmerman
AFGL
Hanscom Air Force Base
Bedford, MA 01731
(612) 861-3476

AGENDA

NASA - USRA

WORKSHOP ON UPPER AND MIDDLE ATMOSPHERIC DENSITY MODELING REQUIREMENTS FOR SPACECRAFT DESIGN AND OPERATIONS

November 19, 20, 21, 1985
Carriage Inn, Huntsville, Alabama

Tuesday, Nov. 19

9:00 - 9:15	Welcome	G. McDonough, NASA/MSF
9:15 - 9:30	Introduction to the WORKSHOP	R. E. Smith, MSFC
9:30 - 12:00	Presentations by the User group	G. Nurre, MSFC
	Satellite Lifetime -	G. Wittenstein, MSFC
	Space Station Reboost -	V. Buckalew, MSFC
	Space Station Momentum Manag.	A. Bordano, JSC
	Hubble Space Telescope Control	G. Nurre, MSFC
	Precision Tracking/Navigation -	USAD/Navy/NORAD
12:00 - 1:00	Lunch	
1:00 - 2:00	Users - Models	H. Buchanan, MSFC
2:00 - 3:00	Orbital Atmosphere Physics	R. Roble, NCAR
	Orbital Atmosphere Dynamics	T. Killeen, U. Mich.
3:00 - 5:00	Modeling	G. Carignan, U. Mich
	A. Hedin, NASA/GSFC (25 min) Emperical Modeling of the Thermosphere: An Overview	
	F. Marcos, AFGL (25 min) Requirements for Improved Modeling of the Thermosphere	
	J. Slowey, Smithsonian (25 min) Limitations to Modeling the Thermosphere and Exosphere	
	Discussion (30 min)	
5:00 - 6:00	Solar Activity - Geomagnetic Indices	J. Joselyn, NOAA
	Solar activity predictions - H. Sargent, NOAA	
	MSFC Solar prediction methods - R. Smith, NASA/MSFC	

Informal discussions in the evening.

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AGENDA

SUB-ORBITAL ATMOSPHERE
Wednesday, Nov. 20

8:30 - 9:30	Summary and conclusions from Day 1	R. E. Smith, NASA/MSFC
9:30 - 11:00	Users Shuttle AOTV (Aero-assisted Orbital Transfer Vehicle) AF/Navy/NORAD	J. Gamble, NASA/JSC
11:00 - 12:00	Users - Models	
12:00 - 1:00	Lunch	
1:00 -	Middle Atmosphere Physics	D.C. Fritts, U.Ak.
- 5:00	Middle Atmosphere Models J. Justus, Georgia Tech K. Champion, AFGL F. Schmidlin, GSFC, Wallops I. J. Findlay NASA/LaRc	S. Bowhill, U. Ill.

Thursday, Nov. 21

8:30 - 10:00	Summary and discussion of Day 2	R. E. Smith
10:00 -12:00	Summaries by Session Chairmen, Discussion	
12:00 - 1:00	Lunch	
1:00 - 3:00	WORKSHOP Conclusions & Recommendations	

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Prepared by Systems Dynamics Laboratory, Science and Engineering Directorate.

*Universities Space Research Association, Boulder, CO.

16. ABSTRACT

A workshop was held on November 19-21, 1985 in Huntsville, Alabama, which dealt with presentations and discussions concerning applications of neutral atmospheric density models to space vehicle engineering design and operational problems. The area of concern which the atmospheric model developers and the model users considered, involved middle atmospheric (50-90 km altitude) and thermospheric (above 90 km) models and their engineering application. Engineering emphasis involved areas such as orbital decay and lifetime prediction along with attitude and control studies for different types of space and re-entry vehicles.

17. KEY WORDS
Middle Atmosphere
Upper Atmosphere
Thermosphere
Atmospheric Density Modeling
Spacecraft Design and Operation
Natural Environment

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DATE

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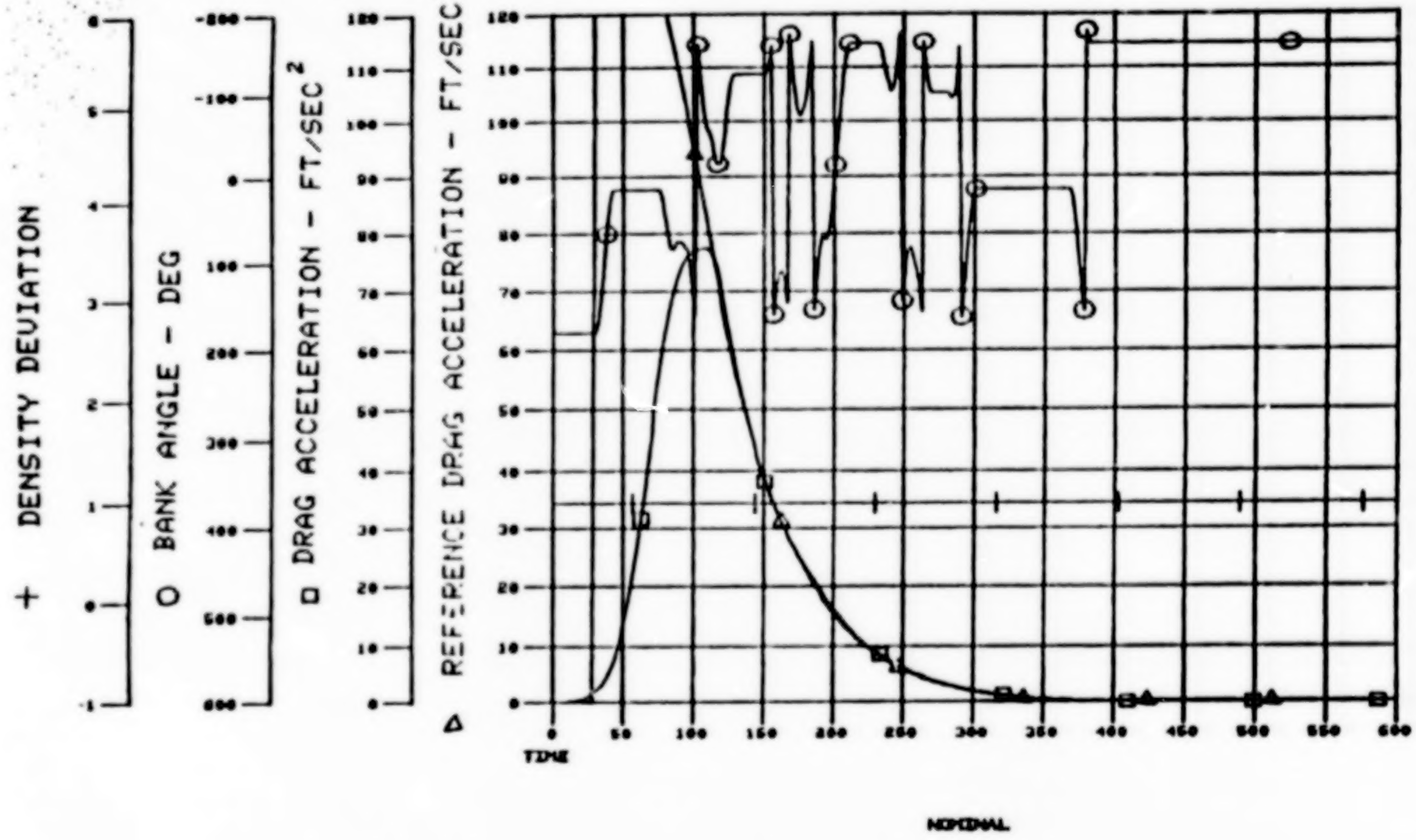
JUN 18 1987

C-3

AFE BASELINE TRAJECTORY



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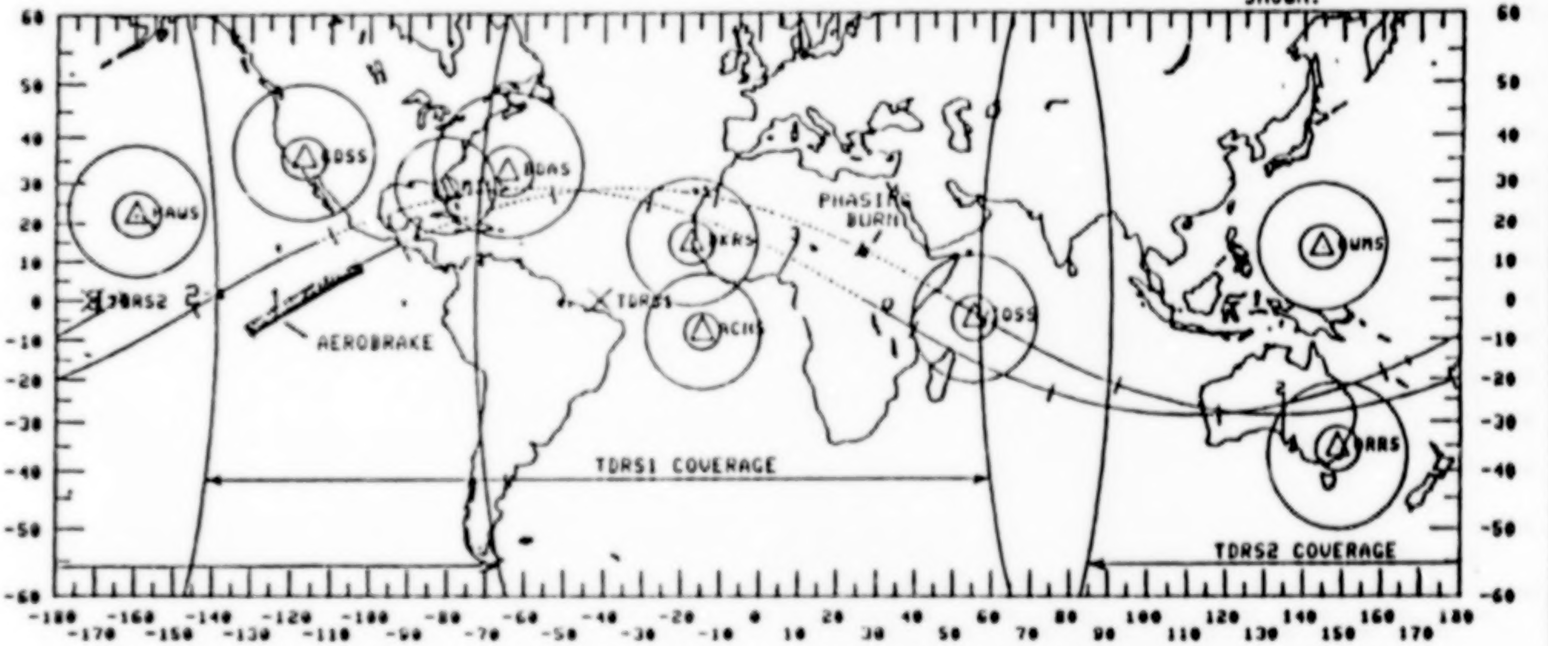
'POST' AFE GROUNDTRACK W/ EXIT AEROBRAKE STATE VECTOR
GTRACE / NASA-A   DATE 10/17/85   TIME 17/48/45   PAGE 1

AFE NOMINAL MANEUVER EVENT SUMMARY

TRACKING STATIONS AND
POSSIBLE TDRS COVERAGE
SHOWN.


HAWS
GDSS
BDAS
MILA
KRS
ACHS
IOSS
GWMS
ORRS
TDRS2
TDRS1
AEROBRAKE
PHASING BURN
TDRS1 COVERAGE
TDRS2 COVERAGE
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180

MNVR	DELTA-V(fps)	PET(H:M:S)	WEIGHT(lbs)	BURN TIME(sec)	PHASE(deg)	MEAN ORBIT(nm)J
BEGIN	-	00:00:00	6292	-	-	160x160
DIRECT ENTRY	9243	00:45:04	2311	77.05	.2	18180x 41
TRIM BURN	111	00:46:41	2276	19.74	1.7	19232x 41
ATM ENTRY	-	00:48:10	2276	-	3.4	19232x 41
ATM EXIT	-	00:57:23	2261	-	8.5	196x 36
PHASING BURN	249	01:30:30	2184	43.02	8.8	196x169

RENDEZVOUS COMPLETE   10:57:42   SHUTTLE DELTA-V• 120fps W/ 9fps SEP

NEXTPAGE 1

AFE AEROBRAKING ANALYSIS

MONTE CARLO ANALYSIS

- 100 GRAM ATMOSPHERIC MODELS ARE GENERATED FOR A SPECIFIED MONTH AND ARE STORED AND CALLED SEQUENTIALLY FOR A 100 TRAJECTORY SIMULATION
- SHUTTLE DERIVED ATMOSPHERES ARE TO BE INCLUDED IN THE MONTE CARLO DATA BASE

AFE AEROBRAKING ANALYSIS

PARAMETRIC DATA

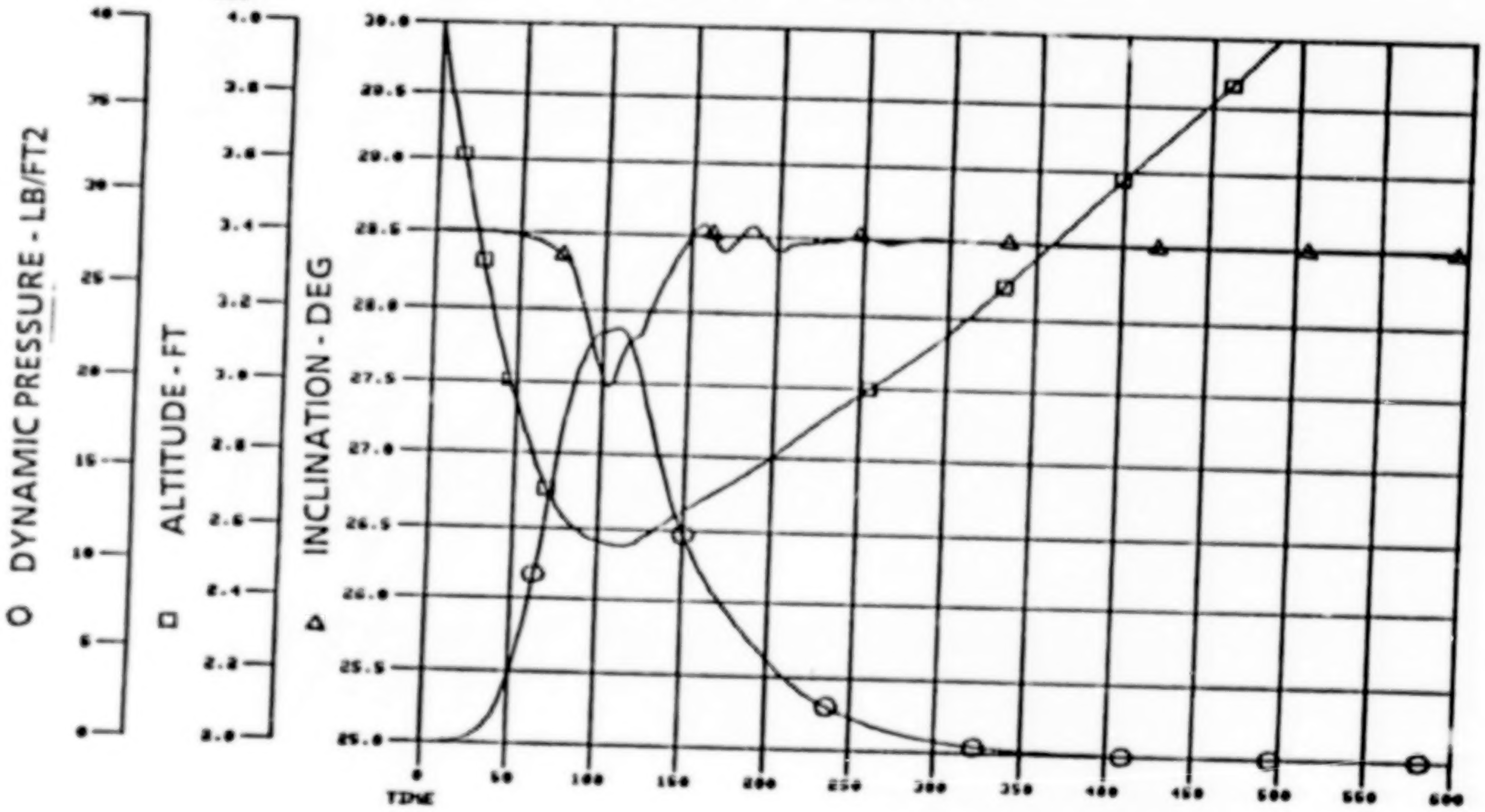
- GRAM MONTHLY MEAN IS USED FOR NOMINAL AEROBRAKING TRAJECTORIES
- SHUTTLE DERIVED ATMOSPHERES (STS 1-14) ARE USED TO SIMULATE DENSITY BIASES AND DENSITY SHEARS ABOUT THE GRAM MONTHLY MEAN ATMOSPHERES
- GRAM DENSITY SHEAR AND DENSITY BIAS
- TRAPAZOIDAL DENSITY SHEARS
  - MAGNITUDE
  - RISE TIME

DRIVERS

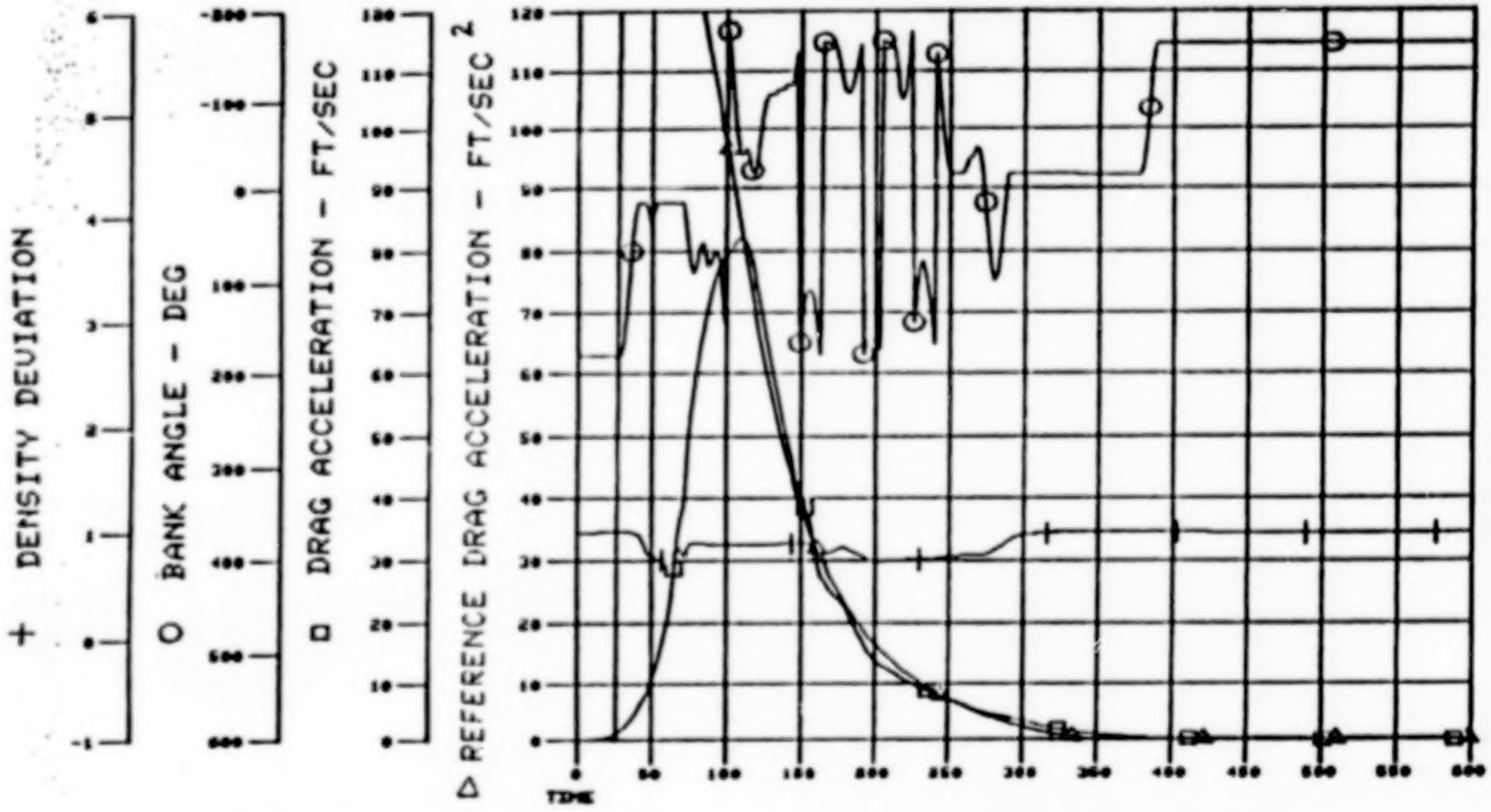
DENSITY GRADIENTS

- MAGNITUDE
- ONSET TIME

AFE BASELINE TRAJECTORY



AFE BASELINE TRAJECTORY



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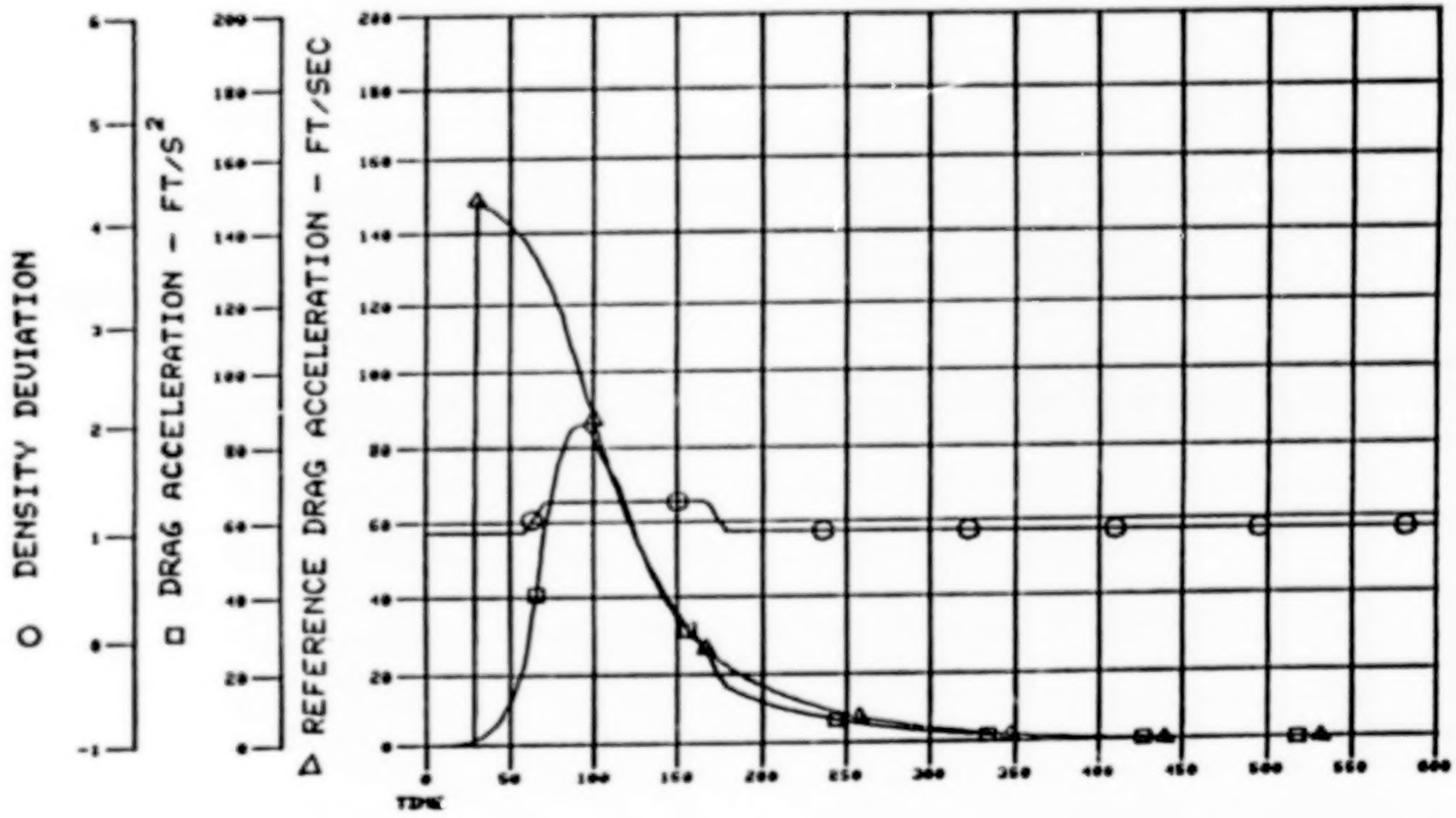
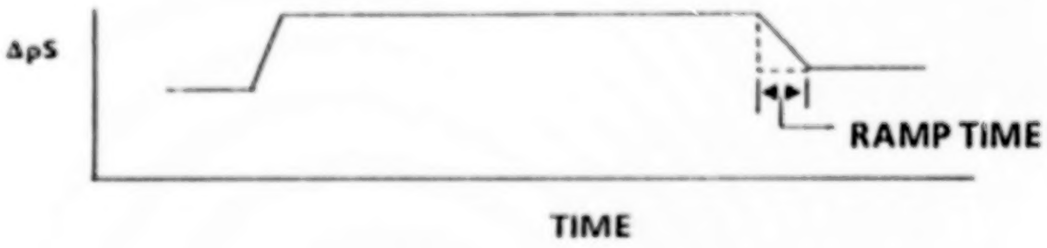
DENSITY SHEAR AT 282 000 FT ALTITUDE

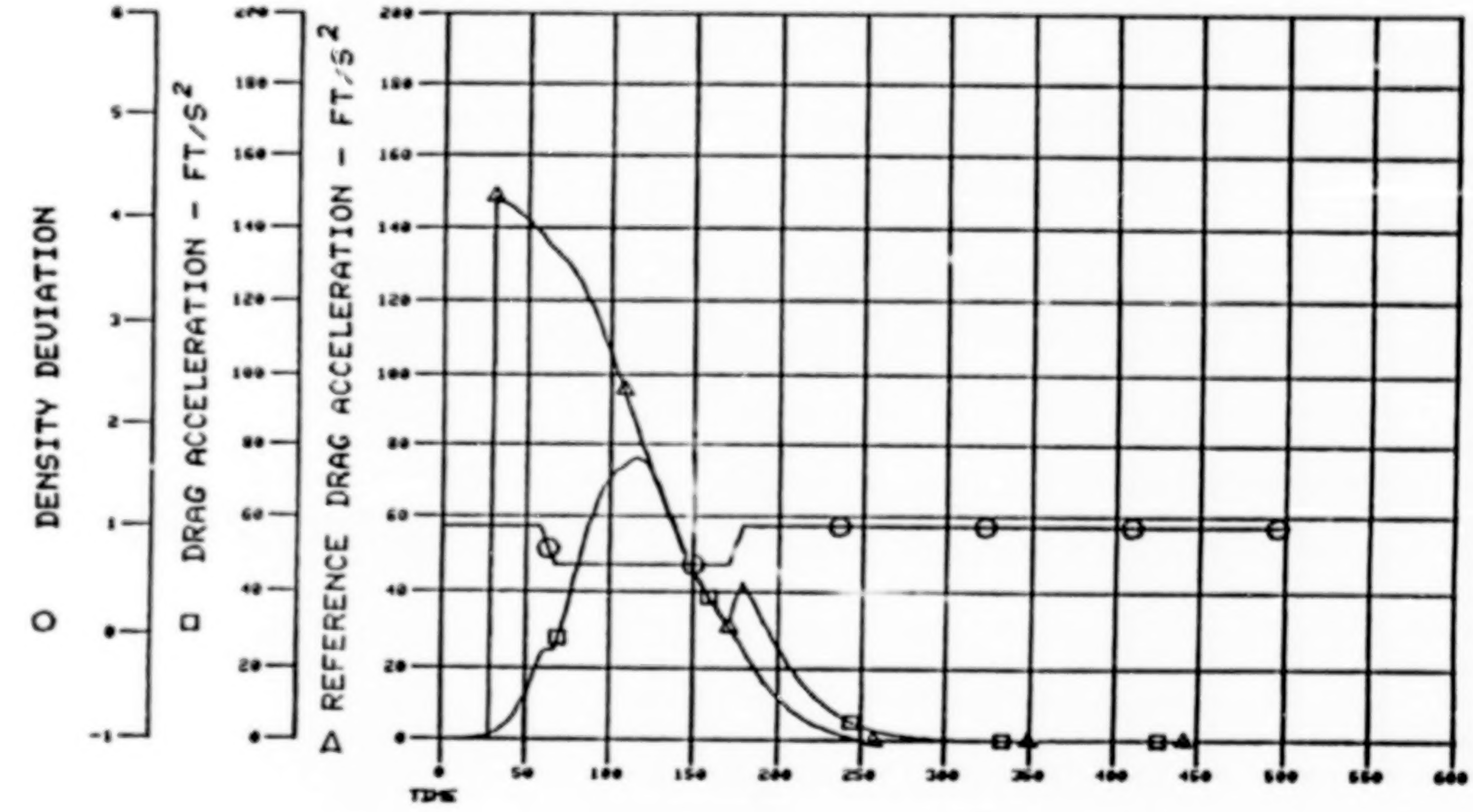


POSITIVE TRAPEZOIDAL DENSITY SHEAR AT 282000 FT.



ΔρS	RAMP TIME SEC	ΔRANGE N.MI.	ΔALTITUDE FT	APOGEE ALTITUDE ERROR N.MI.
20%	2	9	500	-8
30%	4	17	1000	67
30%	8	34	2000	33
30%	12	51	3000	-10
35%	4	17	1000	72
35%	8	34	2000	53
35%	12	51	3000	59
35%	16	68	4000	-5

DENSITY SHEAR AT 282 000 FT ALTITUDE



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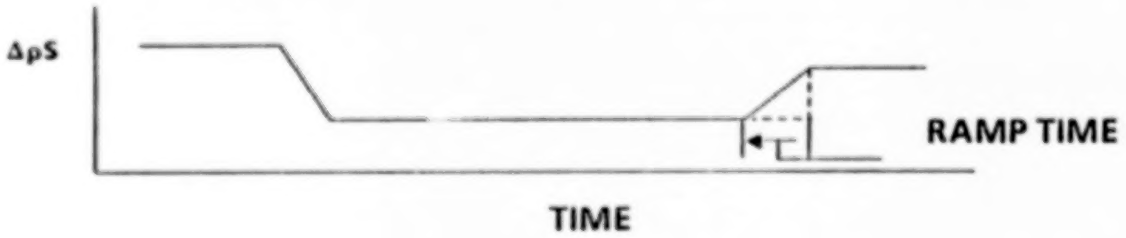
MSD

POSITIVE TRAPEZOIDAL DENSITY SHEAR AT 282000 FT.



ΔρS	RAMP TIME	Δ RANGE	Δ ALTITUDE	APOGEE ALTITUDE ERROR	
	SEC	N.MI.	FT	N.MI.	
20%	2	9	500	-1	
30%	2	9	500	-39	
30%	4	17	1000	-18	
30%	8	34	2000	10	
30%	12	51	3000	11	
35%	4	17	1000	-43	ERATTIC RESULTS
35%	8	34	2000	-2	
35%	12	51	3000	-75	
35%	16	68	4000	9	

MISSION PLANNING AND ANALYSIS DIVISION

GUIDANCE SENSITIVITY TO ATMOSPHERIC DENSITY BIAS

AFE BASE LINE TRAJECTORY

- $\Delta\gamma = +0.20$ DEG, $\Delta\alpha = -2.0$ DEG:

	APOGEE ALTITUDE ERROR - N.MI.
$\Delta\rho = -60\%$	778.5
$\Delta\rho = -50\%$	-13.8
$\Delta\rho = -40\%$	-4.0
↓	
$\Delta\rho = +60\%$	NO EXTREMES

- OTHER $\Delta\gamma$, $\Delta\alpha$ COMBINATIONS HAVE NO EXTREME ERRORS IN APOGEE ALTITUDE FOR $-60\% \leq \Delta\rho \leq +60\%$

CONCLUSION

PROPER DEFINITION OF THE ATMOSPHERE AT THE LOCATION OF THE AEROBRAKING MANEUVER IS CRITICAL TO THE SUCCESS OF THE MISSION

- LOW INCLINATION ORBITS (EQUATORIAL)
- HIGH INCLINATION ORBITS (POLAR)

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OVERVIEW OF SHUTTLE DATA ON DENSITY

Robert Blanchard, NASA/Langley Research Center

The HiRAP (High Resolution Accelerometer Package) used on the Shuttle was described and examples of flight-derived density-altitude profiles were compared to the 1976 Standard Atmosphere. By flying an accelerometer along with a mass spectrometer it is possible to obtain the drag coefficients for the Shuttle. However [Champion] problems may arise due to contamination in the near-shuttle environment.

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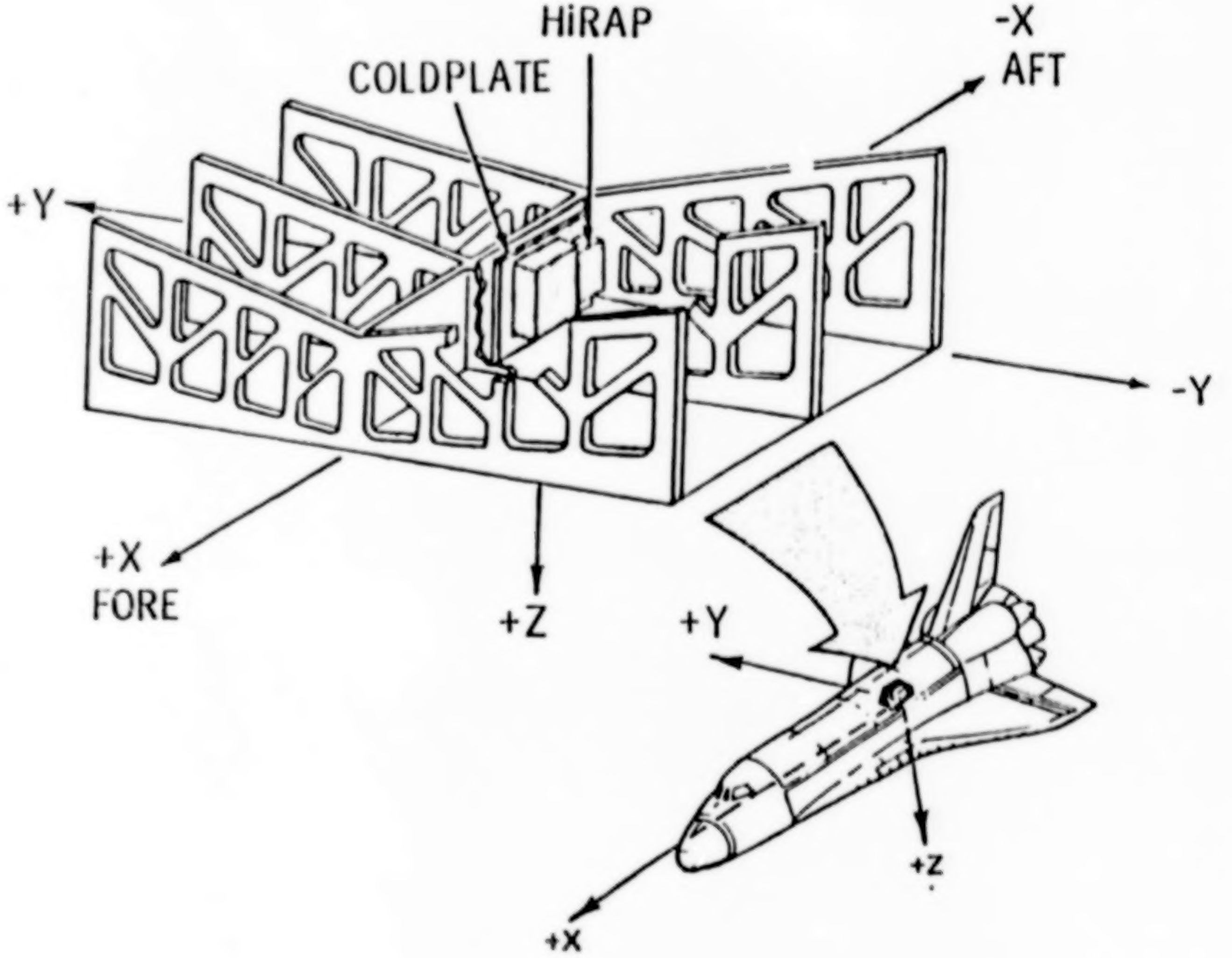
HIGH RESOLUTION ACCELEROMETER PACKAGE (HiRAP) ORIENTATION wrt VEHICLE AXES


HiRAP
COLDPLATE
-X
AFT
+Y
-Y
+X
FORE
+Z
+Y
+Z
+X

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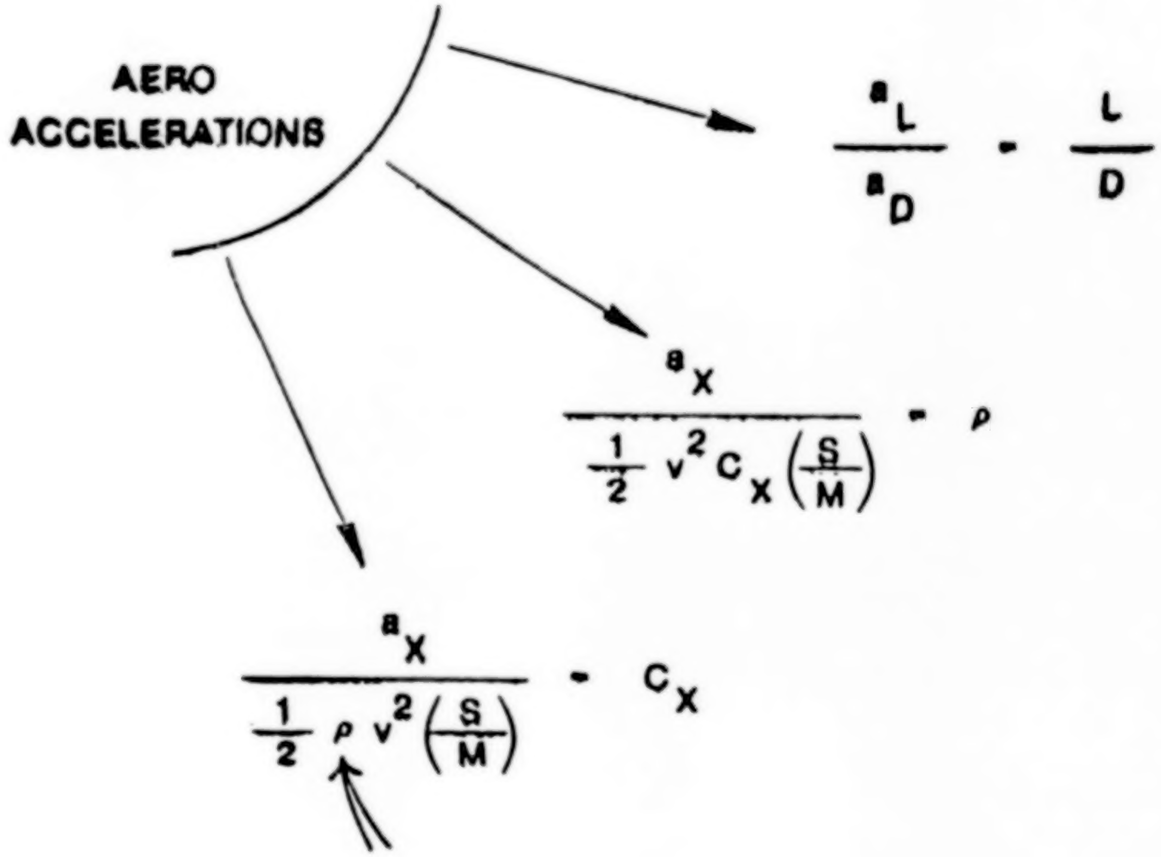
EXPERIMENT CONCEPTS



AERO ACCELERATIONS

$$\frac{a_L}{a_D} = \frac{L}{D}$$

$$\frac{a_X}{\frac{1}{2} v^2 C_X \left(\frac{S}{M}\right)} = \rho$$

$$\frac{a_X}{\frac{1}{2} \underset{\nwarrow}{\rho} v^2 \left(\frac{S}{M}\right)} = C_X$$

JUNE 21

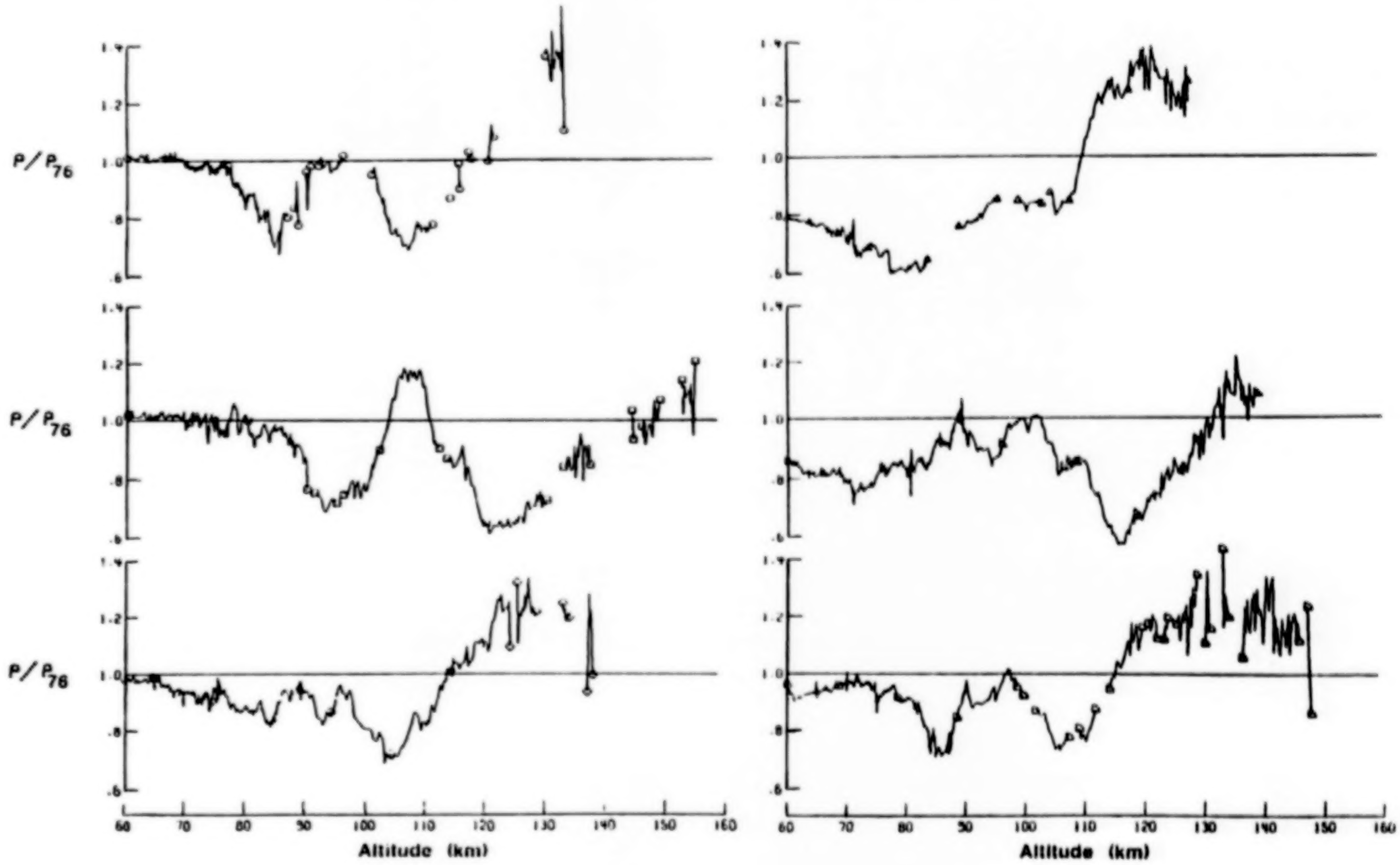
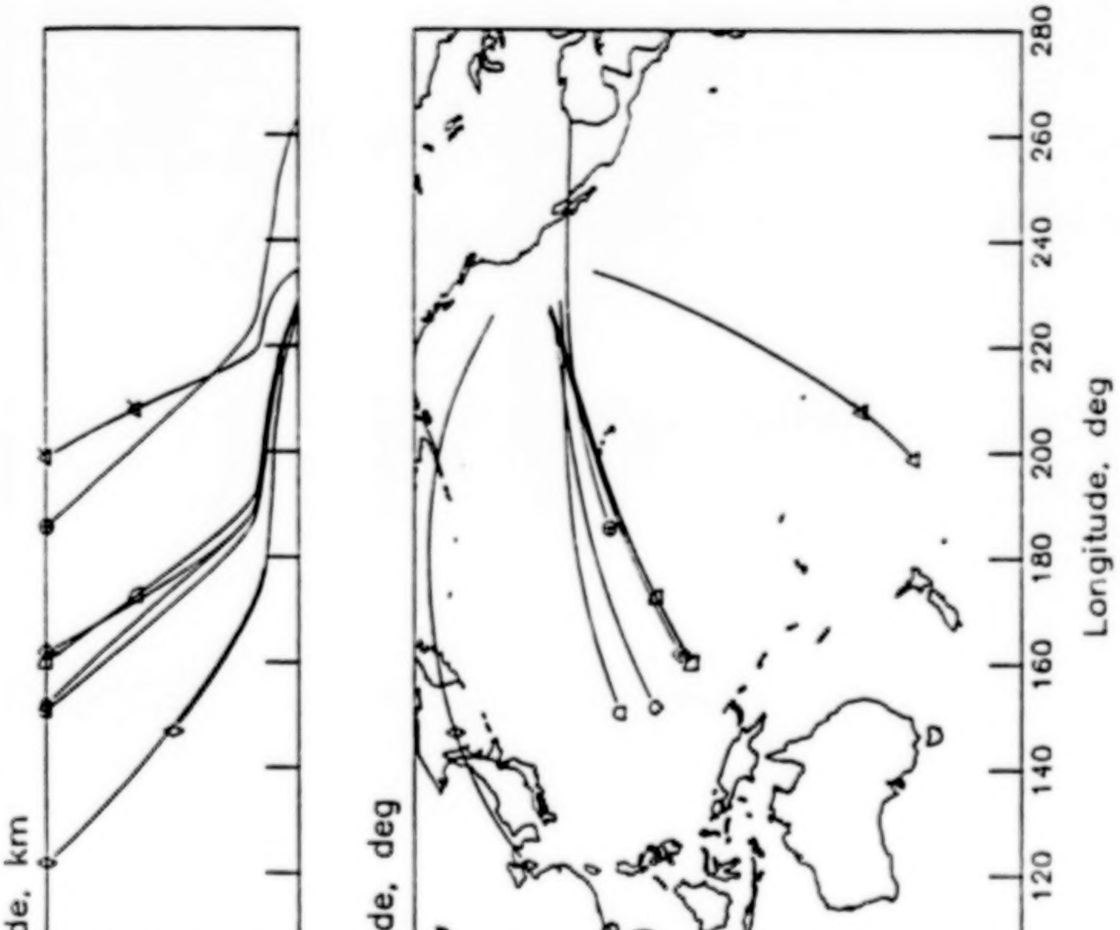


Fig. 12. - Flight derived density altitude profiles.



STS 6–9,11,13,24 Entry Ground Tracks

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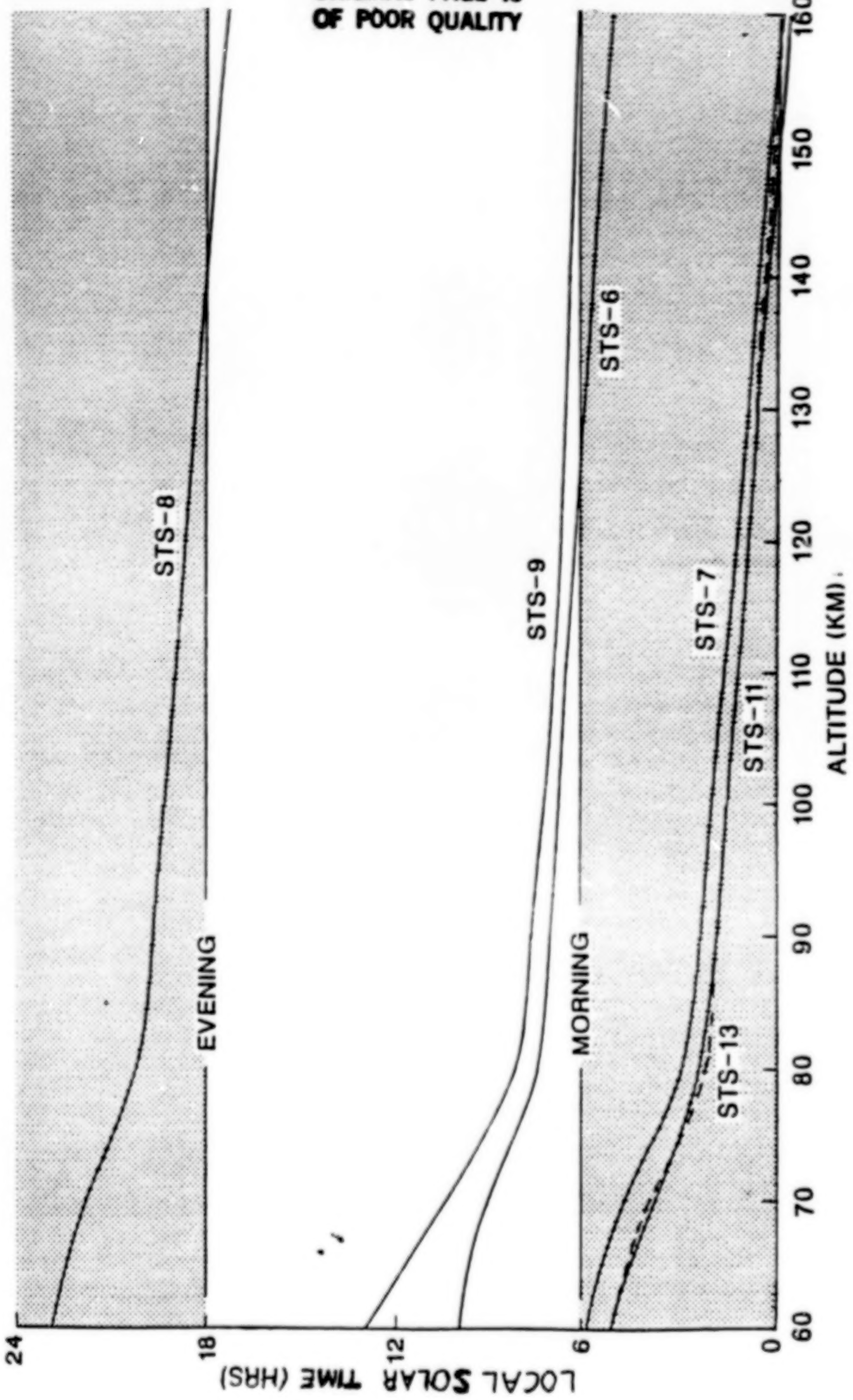

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SHUTTLE DERIVED ATMOSPHERE

John Findlay, Flight Mechanics & Control, Inc.

The shuttle descends along a rather shallow path, thus providing some information on the horizontal structure of the atmosphere. Small scale structures have been suggested (shears, "potholes"). The best estimates of the shuttle drag coefficient and projected areas are used to go from accelerometer data to density through the use of BET's (Best Estimated Trajectories). Data are from the IMU's (Inertial Measurement Unit) and the HiRAP (High Resolution Accelerometer Package).

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SHUTTLE ATMOSPHERE PRESENTATION

AT THE USRA/MSFC JOINTLY SPONSORED WORKSHOP ON

UPPER AND MIDDLE ATMOSPHERIC DENSITY MODELING
REQUIREMENTS FOR SPACECRAFT DESIGN AND OPERATIONS

November 19-21, 1985
Huntsville, Alabama

J. T. Findlay
Flight Mechanics & Control, Inc.

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- Ambient parameters determined as:
  - $\rho_{C_N} = \dfrac{2m\, A_N}{C_{N_P}\, V_A^2\, S_{ref}}$ (sensed density)
  - $dp = -\rho_{C_N}\, g dh$ (hydrostatic eqn)
  - $T = \dfrac{P}{\rho_{C_N} R}$ (perfect gas law)
- Shuttle descent shallow when compared to usual sounding devices thus, implications in the vertical necessarily includes some horizontal structure.
  - profile applicable to vehicles such as AOTV's, ERV's, etc.
  - small scale structure (shears, "potholes") suggested as vertical implications

METHODOLOGY AND LIMITATIONS FOR SHUTTLE DERIVED ATMOSPHERES

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Nov. 1985

DATA SOURCES

- BETs - reconstructed trajectory fit to entry tracking data defining inertial position, velocity and attitude history
- IMUs - mg instruments (tri-redundant set)
- HIRAP - µg instrument
- PRE-OP - ORBITER AERODYNAMIC DATA BASE (vintage 1978, upgrading to '82 pre-Op ADDB)
  - Predicted normal force coefficient good to ±5 percent
- DFI - pressure data for STS-3, STS-5

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COMPARISON SOURCES

- Atmospheric data
  - ROBIN spheres, thermistors - launched in support of entry aerothermodynamic research (time and spatially optimum)
    - Two separate treatments are utilized (by others) to translate these NWS data to the Shuttle ground track and vertical profile
      - Langley Atmospheric Information Retrieval System (LAIRS) files by Price of LaRC
      - NOAA "totem-pole" atmospheres by Gelman of the NWS (for JSC)
- Models (latitudinal and seasonal dependent)
  - GRAM (ρ, T, winds)
  - AF'78 (ρ, T), see Cole, Kantor - USGRL

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Shuttle Flight Data Base

STS	Date
1	April 14, 1981
2	November 14, 1981
3	March 30, 1982
4	July 4, 1982
5	November 16, 1982
6	April 9, 1983
7	June 24, 1983
8	September 5, 1983
9	December 8, 1983
11	February 11, 1984
13	April 13, 1984
14	September 5, 1984
17	October 13, 1984
19	November 16, 1984
23	April 19, 1985
24	May 6, 1985

6 spring
4 summer
5 fall
1 winter

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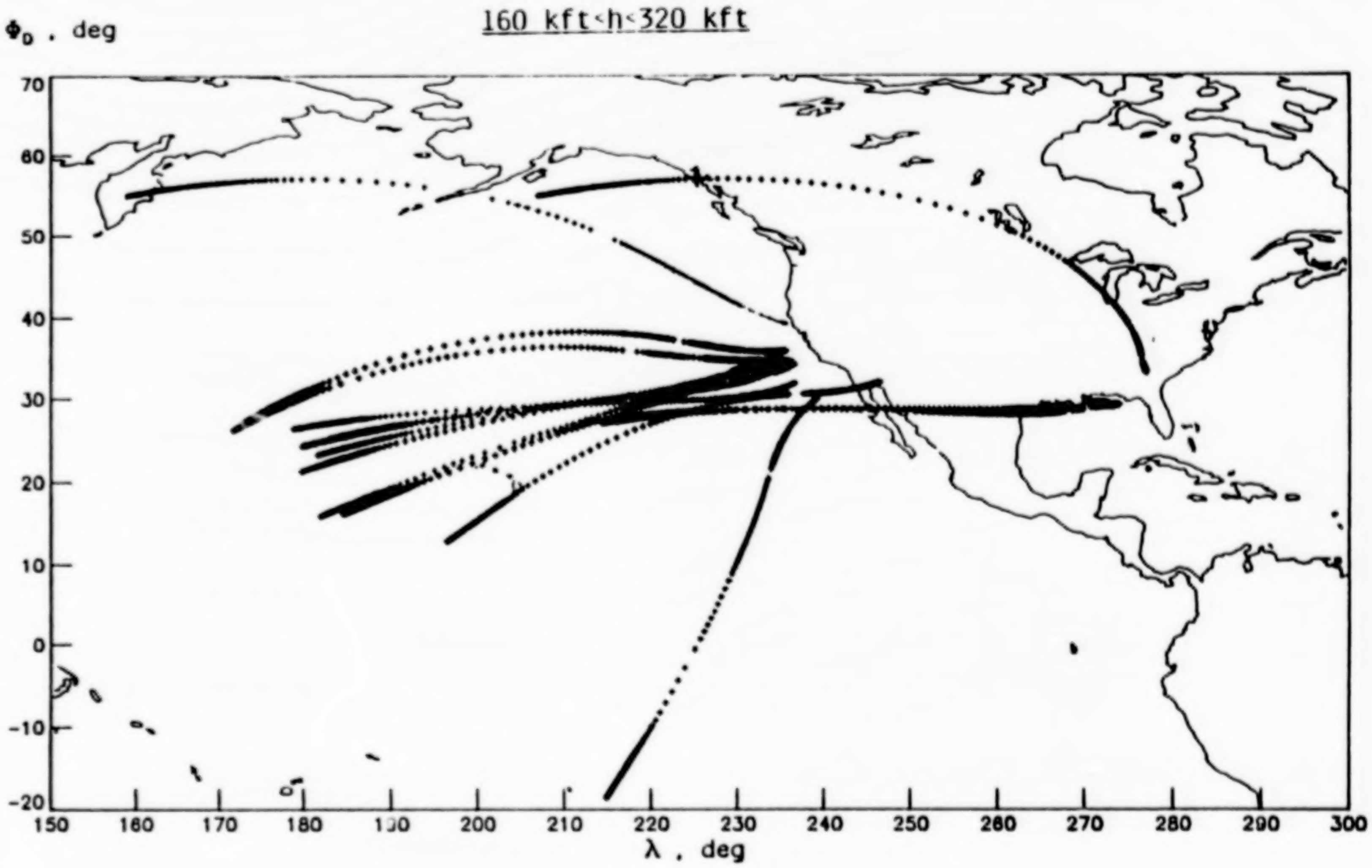
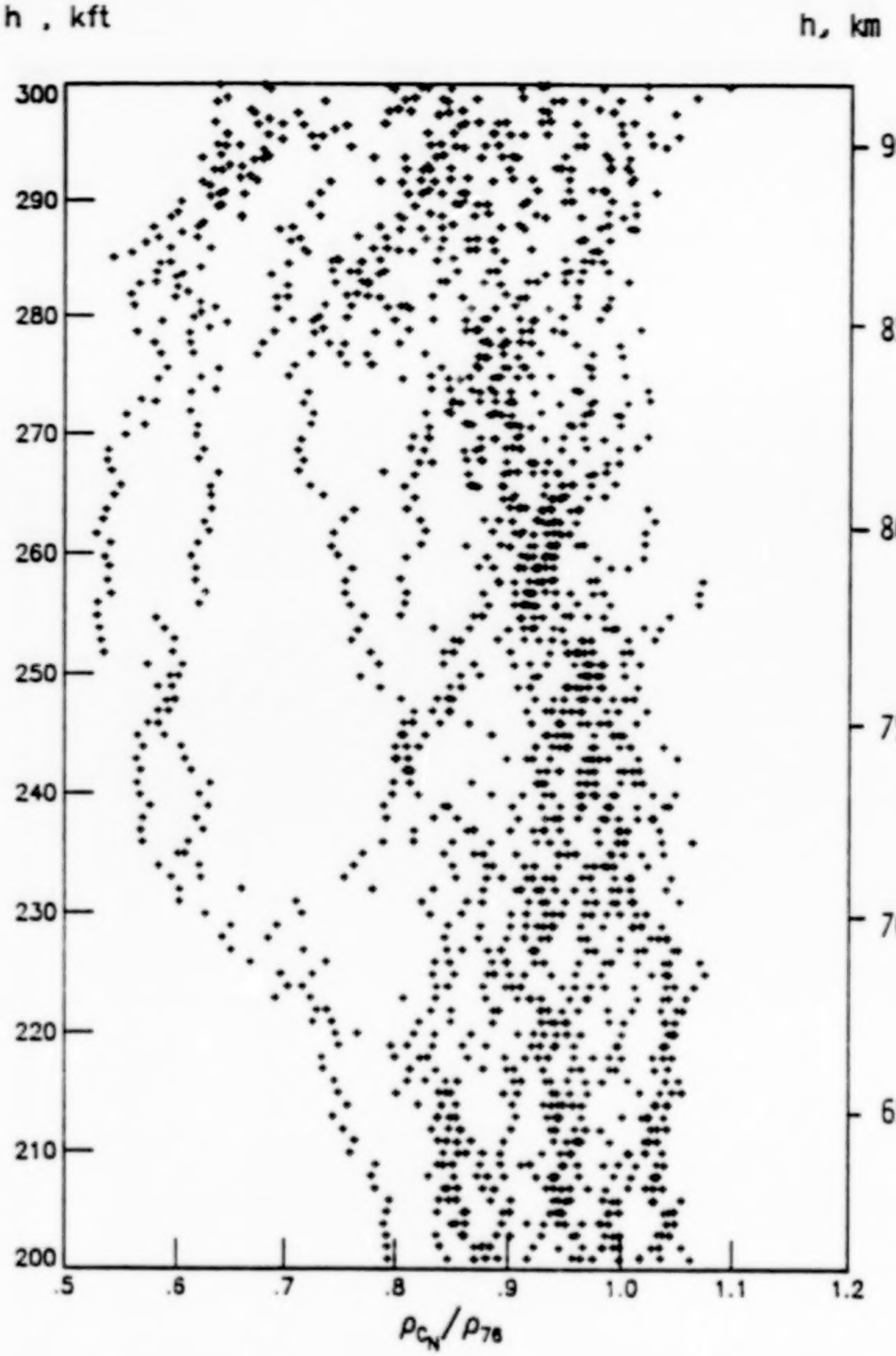

160 kft<h<320 kft
Φ_D , deg
70
60
50
40
30
20
10
0
-10
-20
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
λ , deg

SHUTTLE GROUND-TRACKS IN MIDDLE ATMOSPHERE, 16 FLIGHTS THRU STS-24

JTF-6



SHUTTLE DERIVED DENSITIES IN MIDDLE ATMOSPHERE

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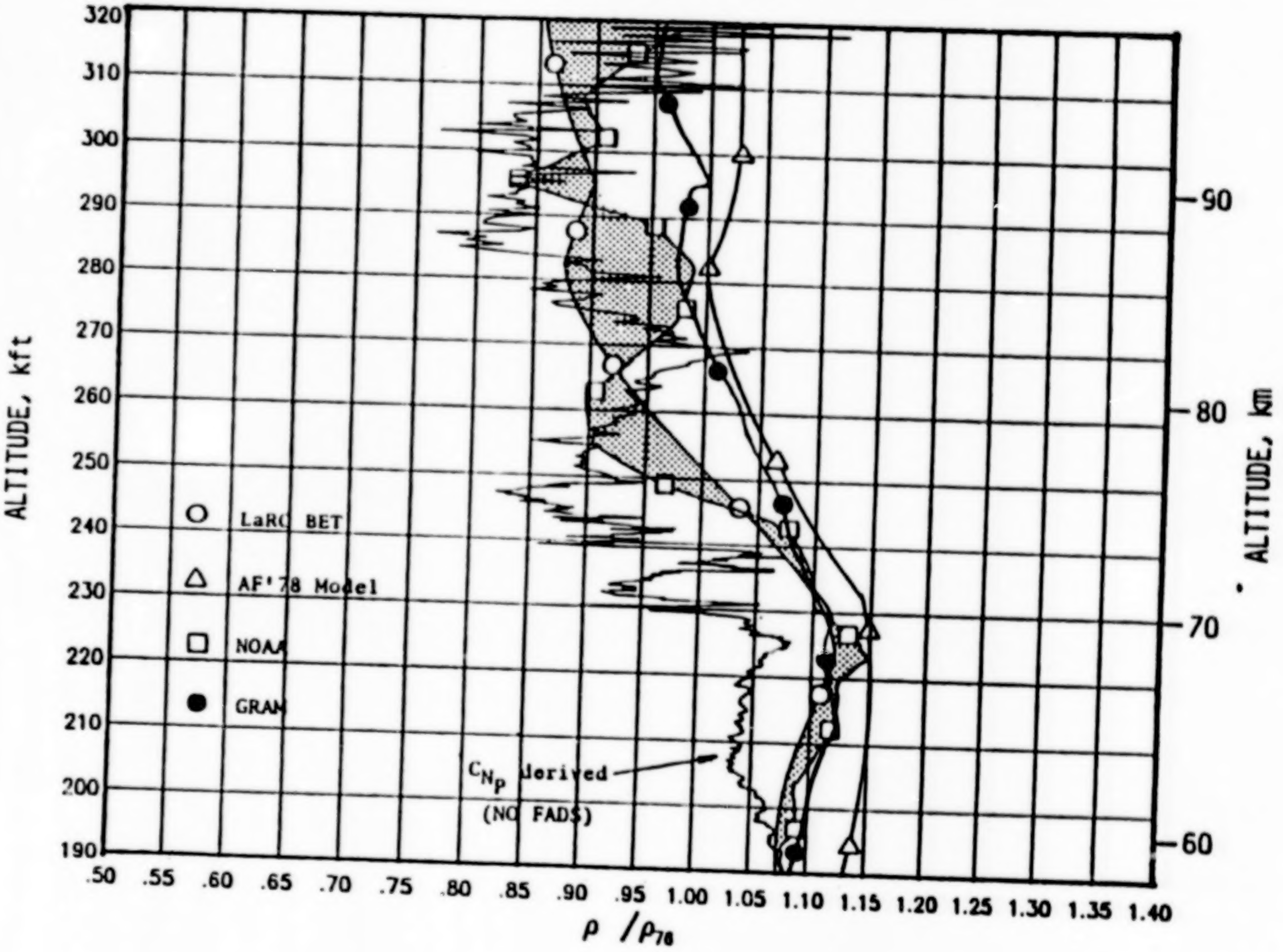

__Typical Summer density comparisons [STS-4, July] showing shear structure in the mesophere.__

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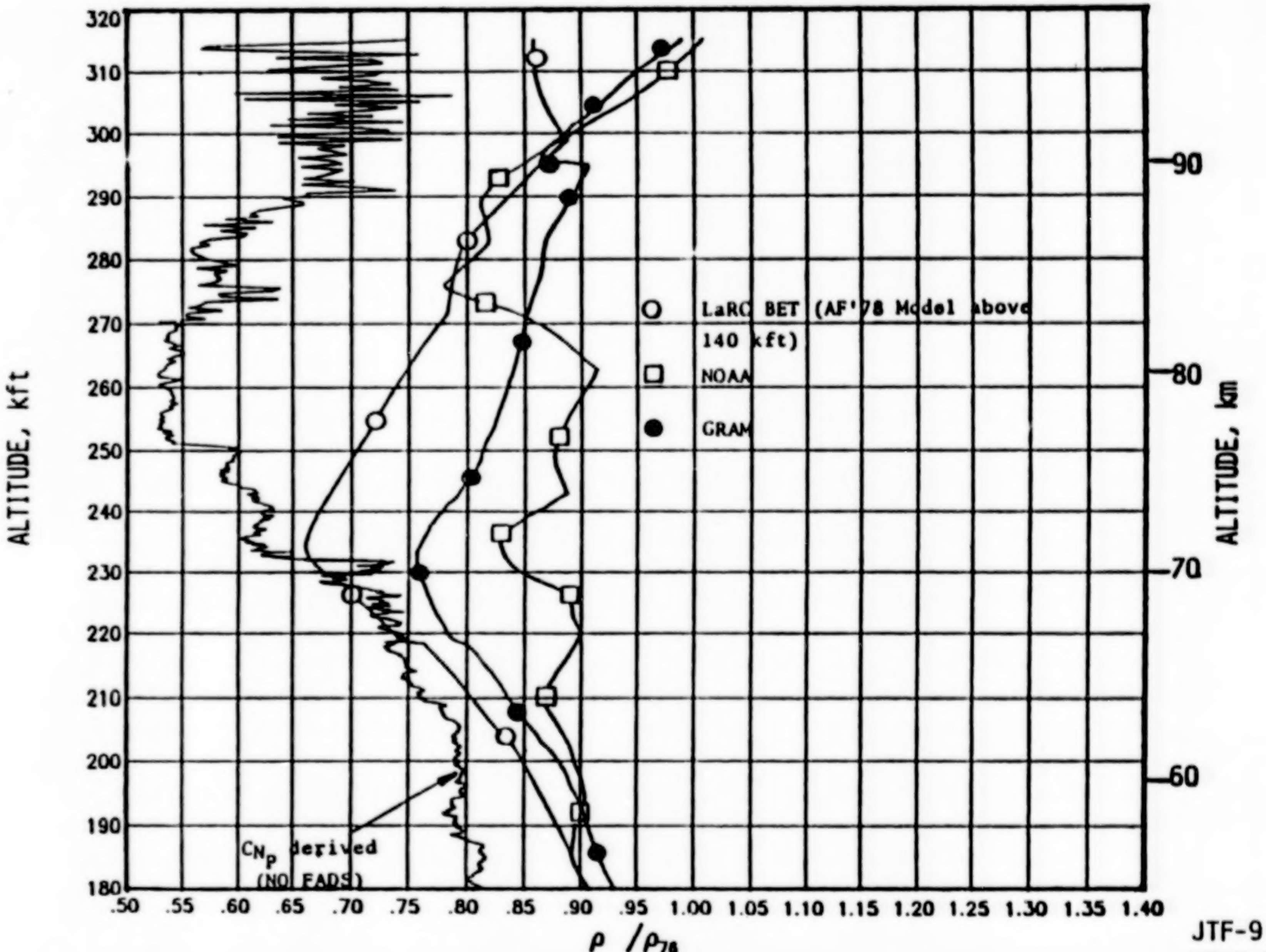

Density comparisons for more Northerly latitudes [STS-9, December]

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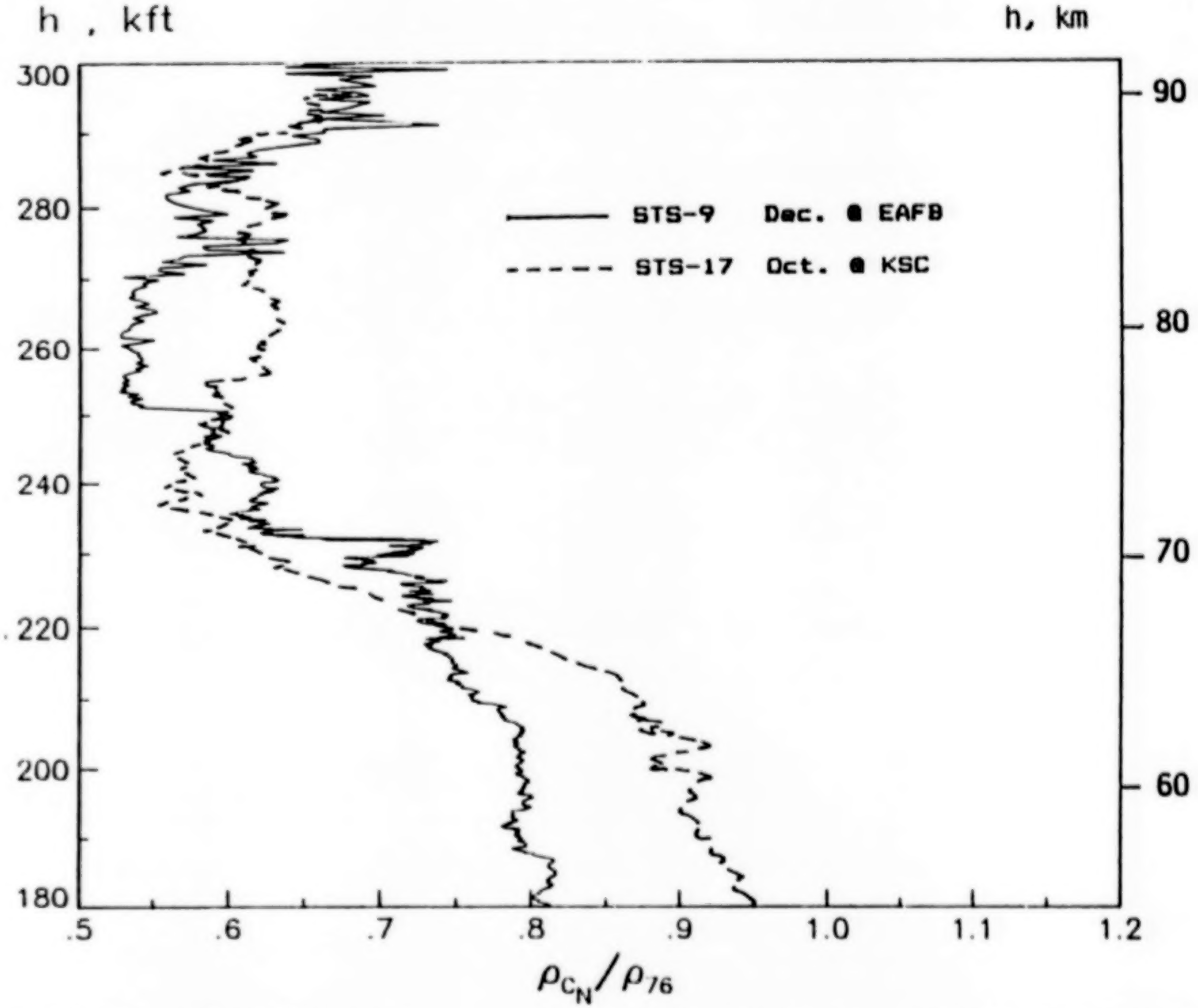

DENSITY COMPARISONS - SHUTTLE HIGH LATITUDE ENTRIES

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FM&C, INC
Nov 19

CONCLUSIONS

- SHUTTLE PROVIDES ACCURATE SOURCE OF ATMOSPHERIC DATA
  - INTERESTING STRUCTURE INDICATED
  - APPLICABLE FOR FUTURE NASA VEHICLE/DESIGN STUDIES
- IMPROVEMENTS SUGGESTED IN MEAN LATITUDINAL/SEASONAL DEPENDENCE OF EXISTING MODELS

JTF-11
FM&C,INC.
Nov. 1985

MIDDLE ATMOSPHERE DYNAMICS

Chairperson: D. Fritts

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GRAVITY WAVES

David Fritts, University of Alaska

Gravity waves contribute to the establishment of the thermal structure, small scale (80-100 km) fluctuations in velocity (50-80 m/sec) and density (20-30%, 0 to peak). Dominant gravity wave spectrum in the middle atmosphere: x-scale, <100 km; z-scale, >10 km; t-scale, <2 hr.

Theorists are beginning to understand middle atmosphere motions. There are two classes: Planetary waves and equatorial motions, gravity waves and tidal motions. The former give rise to variability at large scales, which may alter apparent mean structure. Effects include density and velocity fluctuations (velocity fluctuations are larger), induced mean motions, and stratospheric warmings which lead to the breakup of the polar vortex and cooling of the mesosphere. On this scale are also equatorial quasi-biennial and semi-annual oscillations.

Gravity wave and tidal motions produce large rms fluctuations in density and velocity. The magnitude of the density fluctuations compared to the mean density is of the order of the vertical wavelength, which grows with height. Relative density fluctuations are less than, or of the order of 30% below the mesopause (vertical wavelength of the order of 30 km or less). Such motions may cause significant and variable turbulence and diffusion. Sources include topography, convection, and wind shear. There is a strong seasonal variation in gravity wave amplitude.

Additional observations are needed to address and quantify mean and fluctuation statistics of both density and mean velocity, variability of the mean and fluctuations, and to identify dominant gravity wave scales and sources as well as causes of variability, both temporal and geographic. Useful data can come from satellite measurements - winds, temperatures and constituents; global means and variability, waves and turbulence. Other valuable data can originate from fixed ground sites: radar winds - energies, scales, temporal variability, fluctuation statistics at high resolution; lidar temperatures - wave amplitudes and scales, dynamics, temporal variability at high resolution; optical systems-wavelengths and phase speeds. Relevant measurements include temperature and density, horizontal velocities and wave energies, wave periods, wavelengths, phase speeds, and vertical velocities indicative of trends but not as readily related to density fluctuations.

The GRAM does a good job with the available data. It could be improved substantially with current knowledge if it incorporated better means, i.e. monthly values, and used better fluctuation statistics. Possible alternatives would be based on mean and fluctuation statistics and knowledge of variability to

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rms perturbation horizontal velocity, density, and knowledge of the causes of these perturbations.

Orbital perturbations arise from geomagnetic storms. 250 to 400 percent increases in density at polar latitudes occur under these conditions, giving rise to ten percent fluctuations in orbital velocity. Note that winds are thus not needed unless density variations are known to better than 20 percent.

SUMMARY NOTES - MIDDLE ATMOSPHERE

D. C. Fritts, University of Alaska

1 - MIDDLE ATMOSPHERE OBSERVATIONS:

Beginning to understand middle atmosphere motion; both dynamics and effects

Planetary waves and equatorial motions

Variability at large scales, may alter apparent mean structure

Effects include density and velocity fluctuations (velocity larger) induced mean motions

Stratospheric warmings
Breakup of polar vortex
Cooling of mesosphere

Equatorial quasi-biennial and semi-annual oscillations

Gravity wave and tidal motions

Large rms fluctuations in density and velocity

Magnitude of fluctuations is the order of the vertical wavelength, which grows with height

Wave amplitudes limited by saturation
Mean density fluctuations of the order 0.3 below mesopause (vertical wavelength of the order 30km)

May have small horizontal and temporal scales may cause significant and variable turbulence and diffusion.

RECOMMENDATIONS REGARDING OBSERVATIONS:

Additional studies needed to address/quantify mean and fluctuation statistics, density, and velocity

Variability of mean and fluctuations

Dominant gravity wave scales and sources

Causes of variability, temporal and geographic.

Useful data

- Satellite - winds, temps, constituents
  - Global means and variability, waves and turbulence.
  - Fixed site - winds and temps.
    - Radar winds - energies, scales, temporal variability fluctuation statistics at high resolution
    - Lidar temperatures. - wave amplitudes and scales, dynamics, temporal variability. at high resolution
    - Optical systems - wavelengths and phase speeds
- Relevant measurements
  - Temperature and density
  - Horizontal velocities and wave energies
  - Wave periods, wavelengths, phase speeds
  - Vertical velocities indicative of trends, but not as readily related to density fluctuations.

2 - DATA USE/MODEL IMPLEMENTATION:

GRAM Model

- Good job with available data
  - Can improve substantially with current knowledge
    - Better means, use monthly values
    - Better fluctuation statistics
  - Alternatives possible
    - Based on mean and fluctuation statistics
    - Knowledge of variability in rms velocity fluctuation components and density fluctuations, along with causes.

3 - ORBITAL PERTURBATIONS:

Geomagnetic storms
- ~250-400% increases in density at polar latitudes
- ~10% orbital velocity fluctuations

Thus winds not needed unless density variations known to ~20%

MIDDLE ATMOSPHERE MODELING

Chairperson: S. Bowhill

CONCLUSIONS ON MIDDLE ATMOSPHERE MODELING

S. Bowhill, University of Illinois

COMMENT: GRAVITY WAVE CLIMATOLOGY

A climatology of gravity waves is needed, along with a means for incorporation of winds into the models.

ISSUE 1: AVAILABILITY OF NEW DATA

During the past 10 years, a substantial body of new data has become available relating to the structure and dynamics of the atmosphere between 10 and 100 km altitude, which should be taken into account in preparing new models of this region, as follows:

A. Satellite radiometry. Models have been prepared (for example, BARNETT and CORNEY, 1985) based entirely on satellite data, that are quite comprehensive in geographical coverage though limited in altitude extent (up to 80 km only). However, the published models lack information about the dispersion of the results around the monthly mean values: this information is available from the original tapes.

We recommend that this dispersion information be added to the available satellite model information.

B. Rayleigh-scatter lidar. This new technique (CHANIN et al., 1985) is capable of giving density and temperature data over the altitude region 35-80 km with good accuracy, but from a fixed ground location. These data may be useful for real-time ground truth. Gravity-wave data are also derived but with lesser time resolution than with MST radars (see below).

We recommend that the capabilities of this technique be augmented and that additional information be provided.

C. MST radar. The mesosphere-stratosphere-troposphere radar (ROTTGER, 1984) is useful for winds (1 hr resolution) and gravity-wave measurements (1 min resolution) from 5 to 25 km altitude, and (in the daytime only) from 60 to 95 km altitude.

We recommend that present MST radars be used to develop detailed climatologies for gravity waves in the region between 60 and 95 km altitude, including seasonal, geographic, orographic and meteorological effects.

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D. Orbiter drag. Since the shuttle orbiter spends a considerable portion of its re-entry track at around 200,000 to 250,000 ft. altitude, accelerometer data from this source can provide unique information about the horizontal structure of gravity waves.

We recommend intensive study of those measurements.

E. Occultation of astronomical objects. Considerable success has been obtained in using occultation of X-ray sources using observatory satellites such as HEAO-2 (MATTHEWS, 1985) to determine atmospheric densities in the 85-150 km height range. The Navy SHAD program accomplishes the same objective at a lower altitude by observing the refraction of visible sources.

We recommend that the feasibility of incorporating densities determined from occultation data be investigated.

ISSUE 2: IMPROVEMENT OF THE GRAM MODEL

The GRAM model, in the altitude region below 100 km, is based primarily on the model of GROVES (1971). Considering that it used no satellite data, the model is surprisingly realistic. However, some further work is needed to improve it, as follows:

A. Gross features. Comparisons of the density and temperatures of the GRAM model with those of the satellite model of BARNETT and CARNEY (1985) have shown some difference.

We recommend that the GRAM model be adjusted to reflect the zonal means for standing planetary waves 1 and 2 from the Barnett and Corney model.

B. Fine structure. The dispersions in the GRAM model are prepared primarily on rocket measurements.

We recommend that dispersions from the satellite data base be incorporated.

C. Monte-Carlo simulation. The Markov process used to generate the irregular structure in the GRAM model does not give a realistic representation of gravity-wave irregularities in the mesosphere; nor does it provide the correct spatial spectrum at high frequencies.

We recommend that an alternate procedure for irregularity simulation be developed, resulting in realistic distribution functions and correlation functions.

ISSUE 3: POSSIBILITY OF REAL-TIME DATA INPUT

In principle, given the large overall variability in mesospheric-atmospheric density (particularly in winter and at high latitudes), measurements of mesospheric density in real time could greatly improve the model predictions. However, the practicality of incorporating such measurements is very much in question. It is possible that incorporating a limited number of alternate scenarios for re-entry might produce a cost-effective improvement in re-entry margins.

We recommend investigation of the feasibility of incorporating re-entry data into the re-entry plan, including time of year, geographic location; storm environment and the transient planetary-wave pattern.

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Chanin, M.L., A. Hauchecorne, and M. Smires (1985), Contribution to the CIRA model from ground-based lidar, Handbook for MAP, Vol 16, 305-314, SCOSTEP Secretariat, Dep. Elec. Computer Eng., Univ.of IL, Urbana-Champaign.

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Rottger, J. (1984), The MST radar technique, Handbook for MAP, Vol. 13, 187-232, SCOSTEP Secretariat, Dep. Elec. Computer Eng., Univ.of IL, Urbana-Champaign.

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THE GRAM-III MODEL

C. G. Justus, Georgia Institute of Technology

The GRAM is under continuous development and improvement. GRAM data were compared with Middle Atmosphere Program (MAP) predictions and with shuttle data (Blanchard).

An important note: Users should employ only step sizes in altitude that give vertical density gradients consistent with shuttle-derived density data. Using too small a vertical step size (finer than 1 km) will result in what appears to be unreasonably high values of density shears but what in reality is noise in the model.

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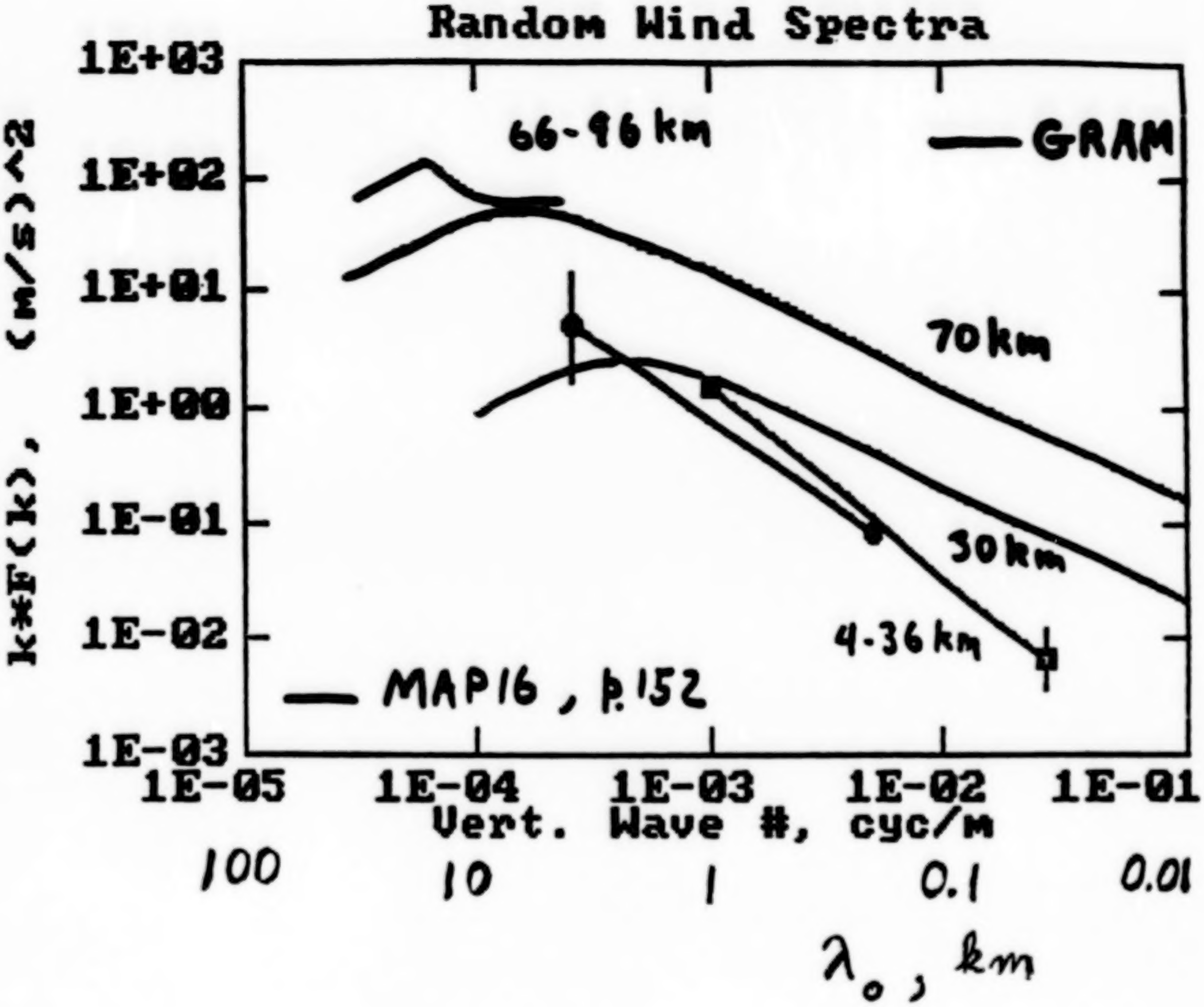

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$$\rho(z+\Delta z) = r_\rho(\Delta z)\,\rho(z) + \beta\,\sigma_\rho\,w_z$$

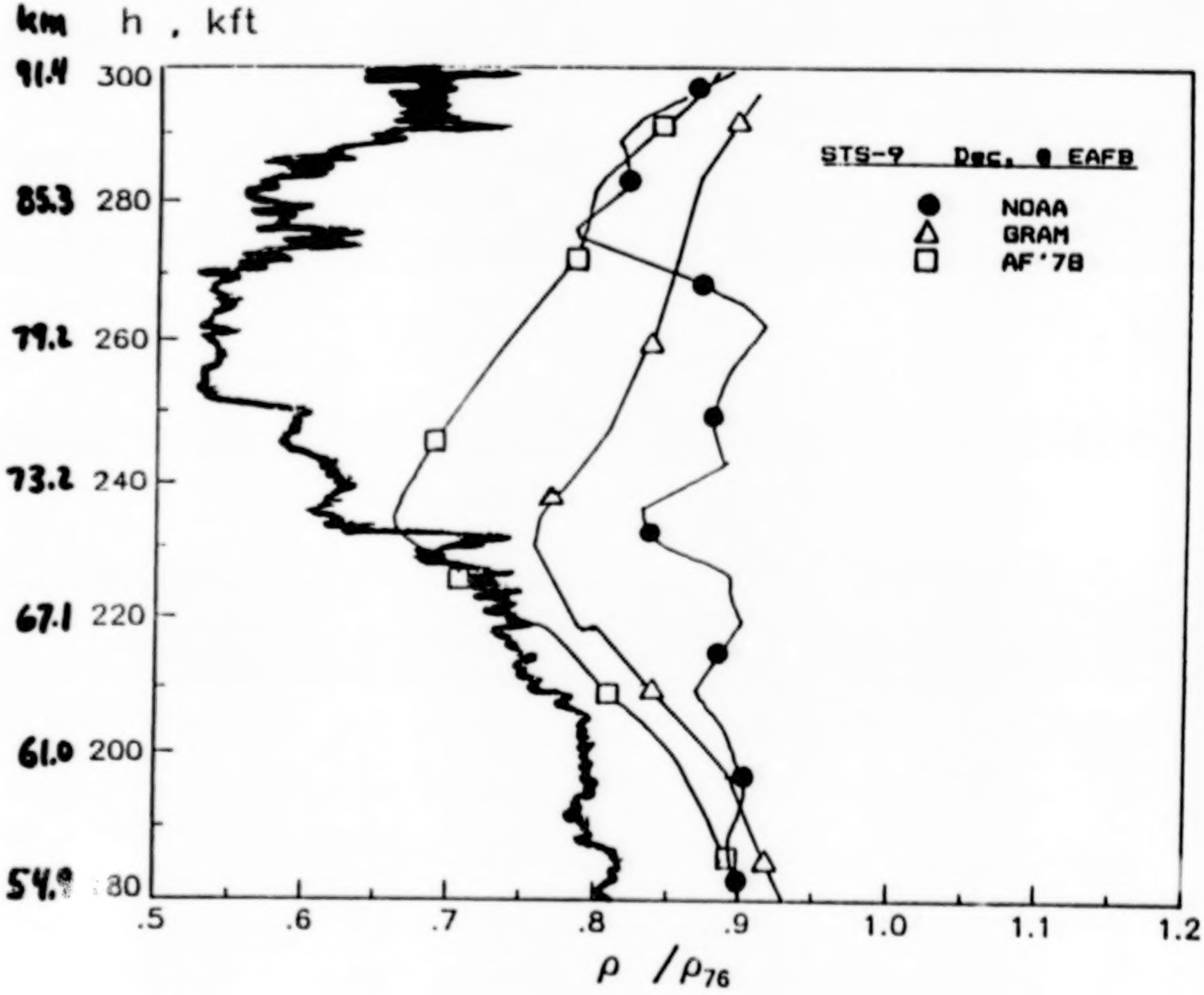
$$\beta = \sqrt{1 - r_\rho^2(\Delta z)}$$

$$r_\rho(\Delta z) = e^{-\Delta z/L}$$

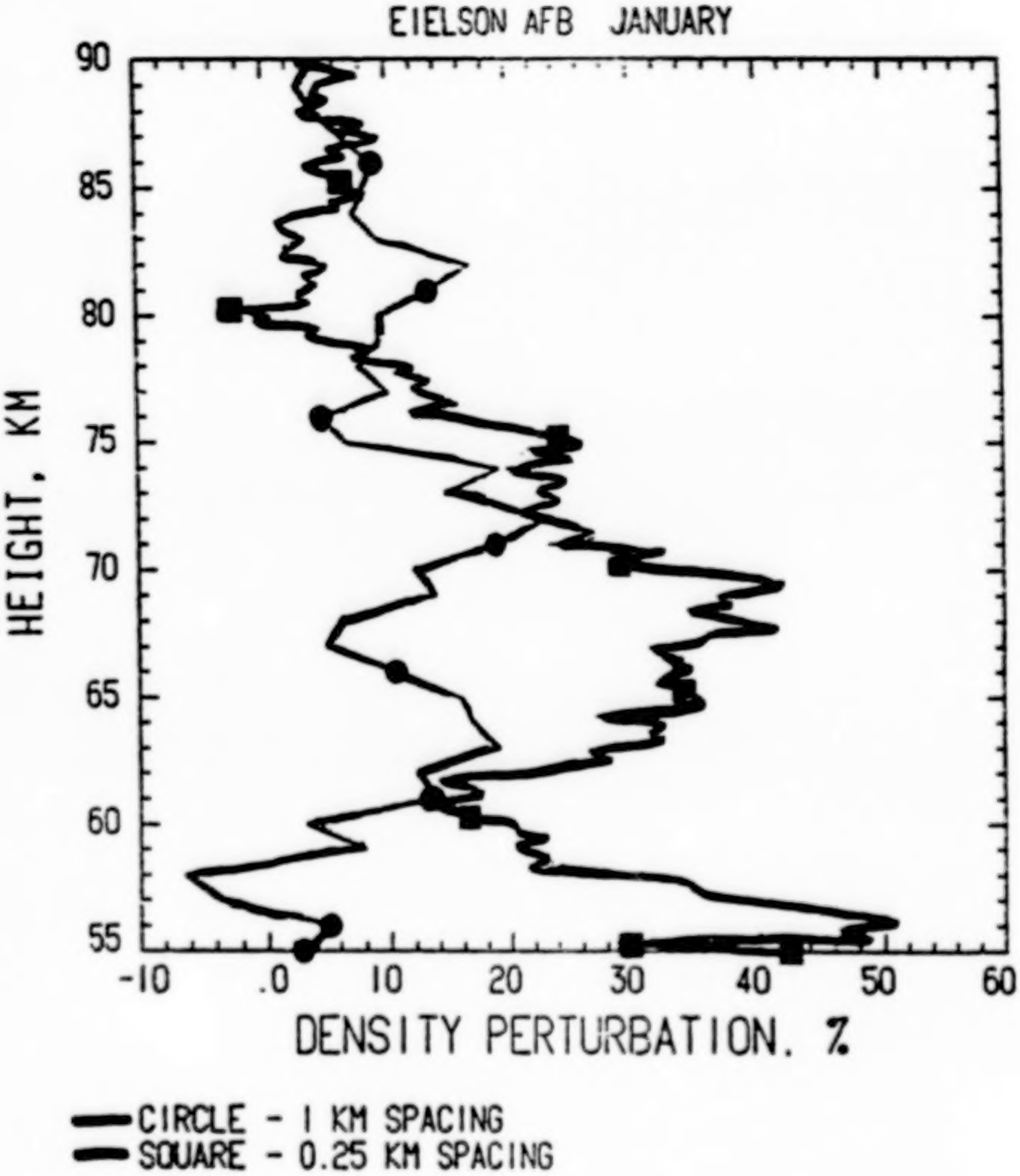
$$\Delta\rho = \rho(z+\Delta z) - \rho(z)$$

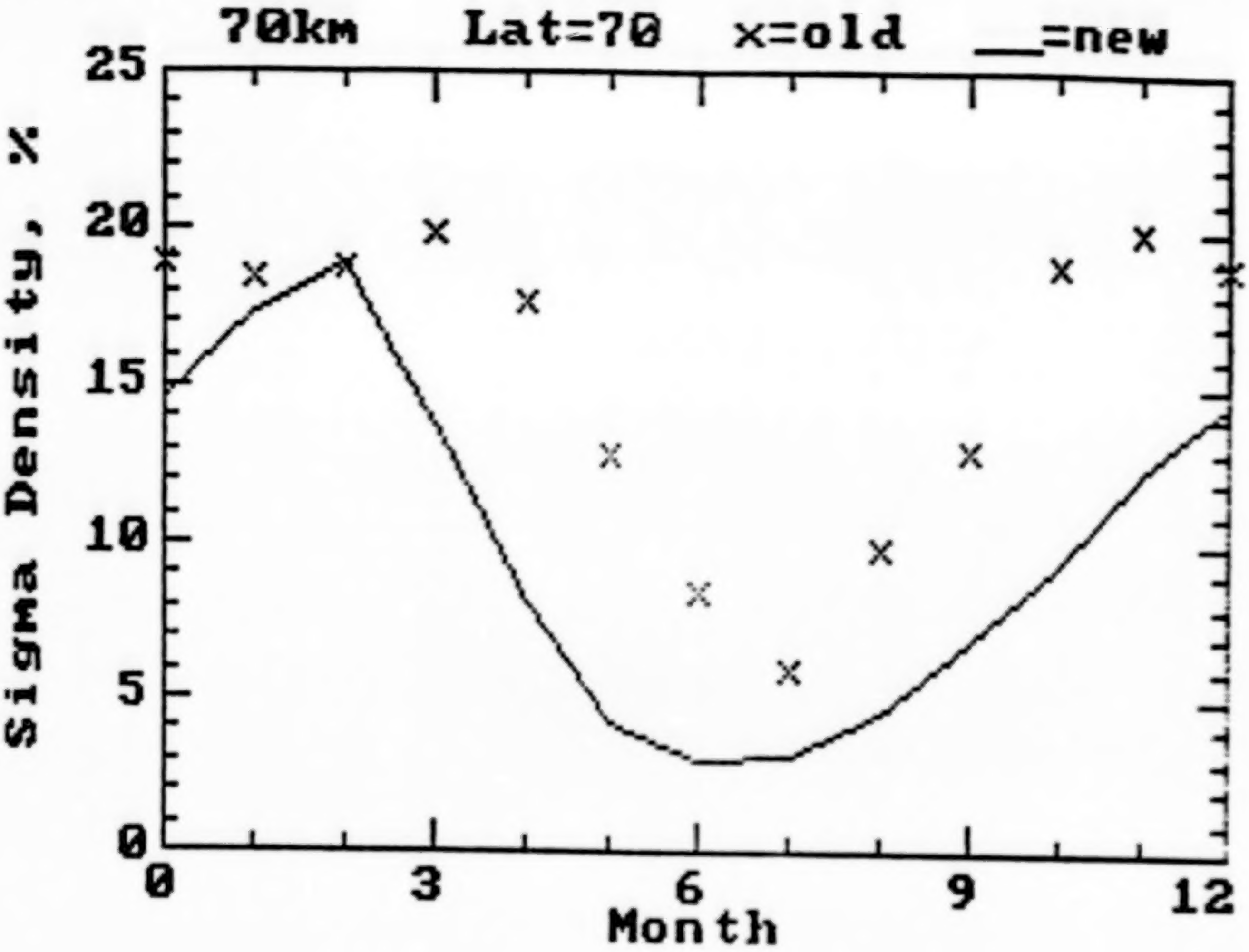
$$\left.\begin{aligned} \overline{(\Delta\rho)^2} &\to 2\,\sigma_\rho^2\,\Delta z/L \\ \overline{(\Delta\rho/\Delta z)^2} &\to 2\,\sigma_\rho^2/\Delta z L \end{aligned}\right\}\ \Delta z/L \to 0$$

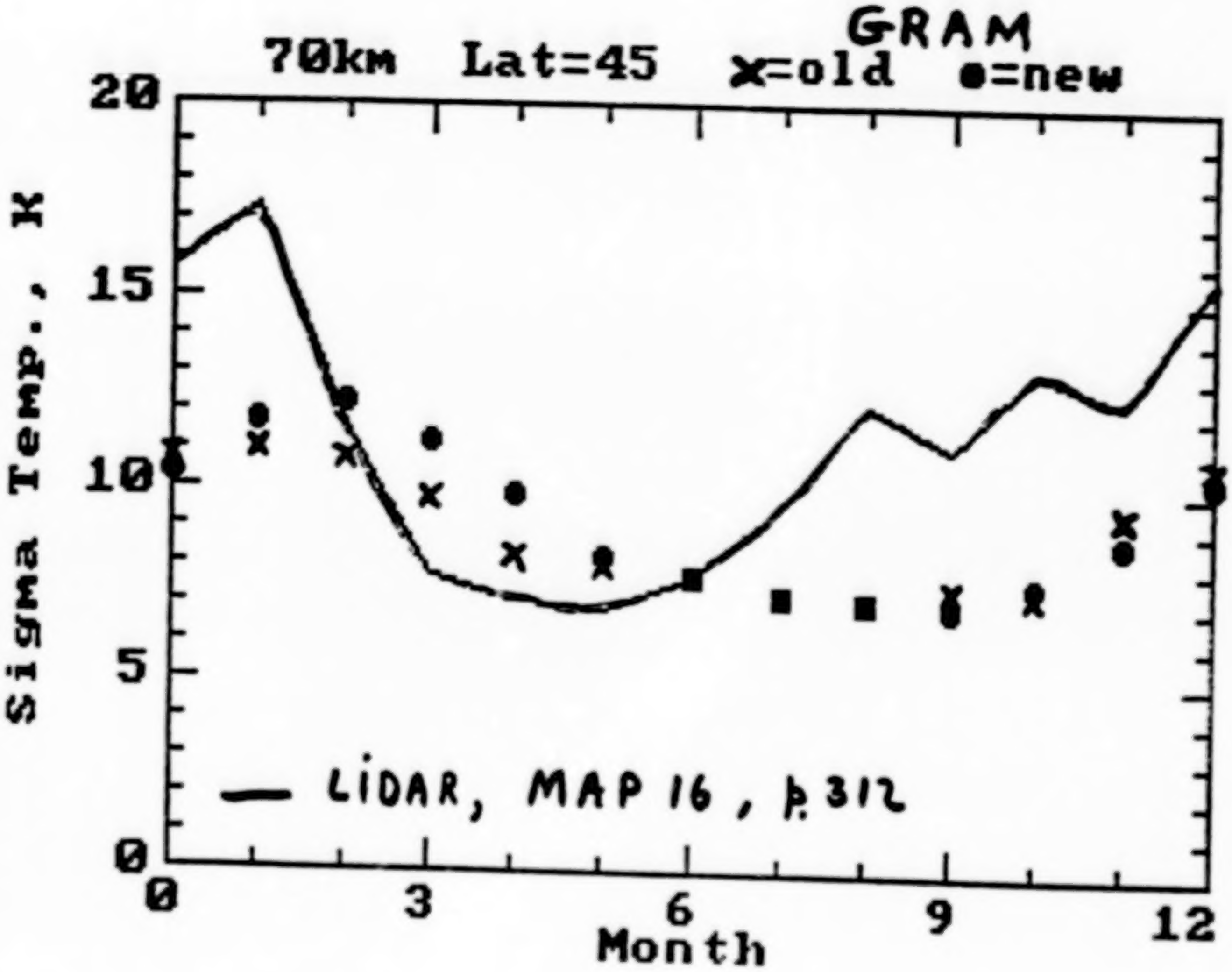
$$E_\rho(k) \sim k^{-2} \qquad kL \to \infty$$

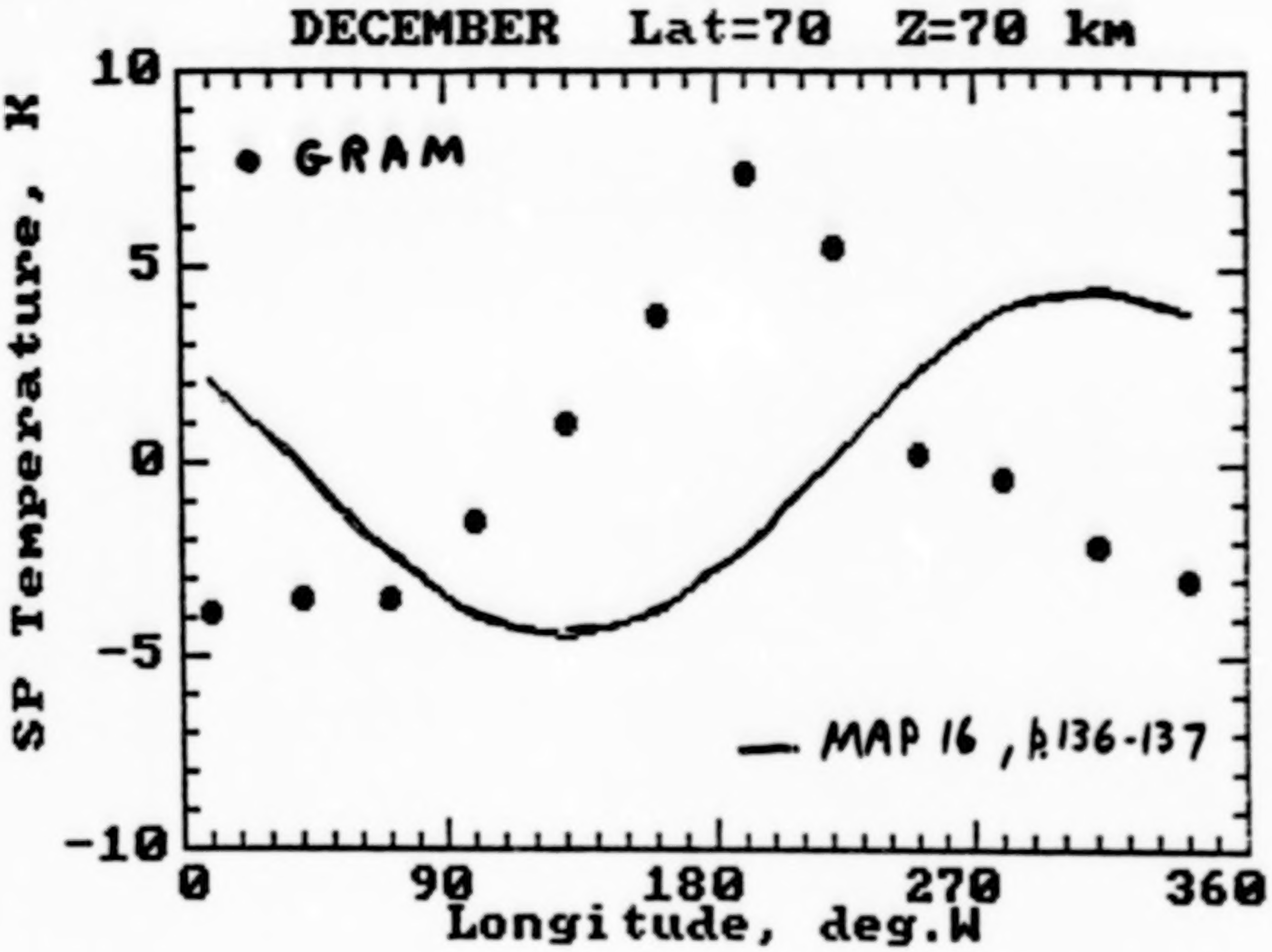


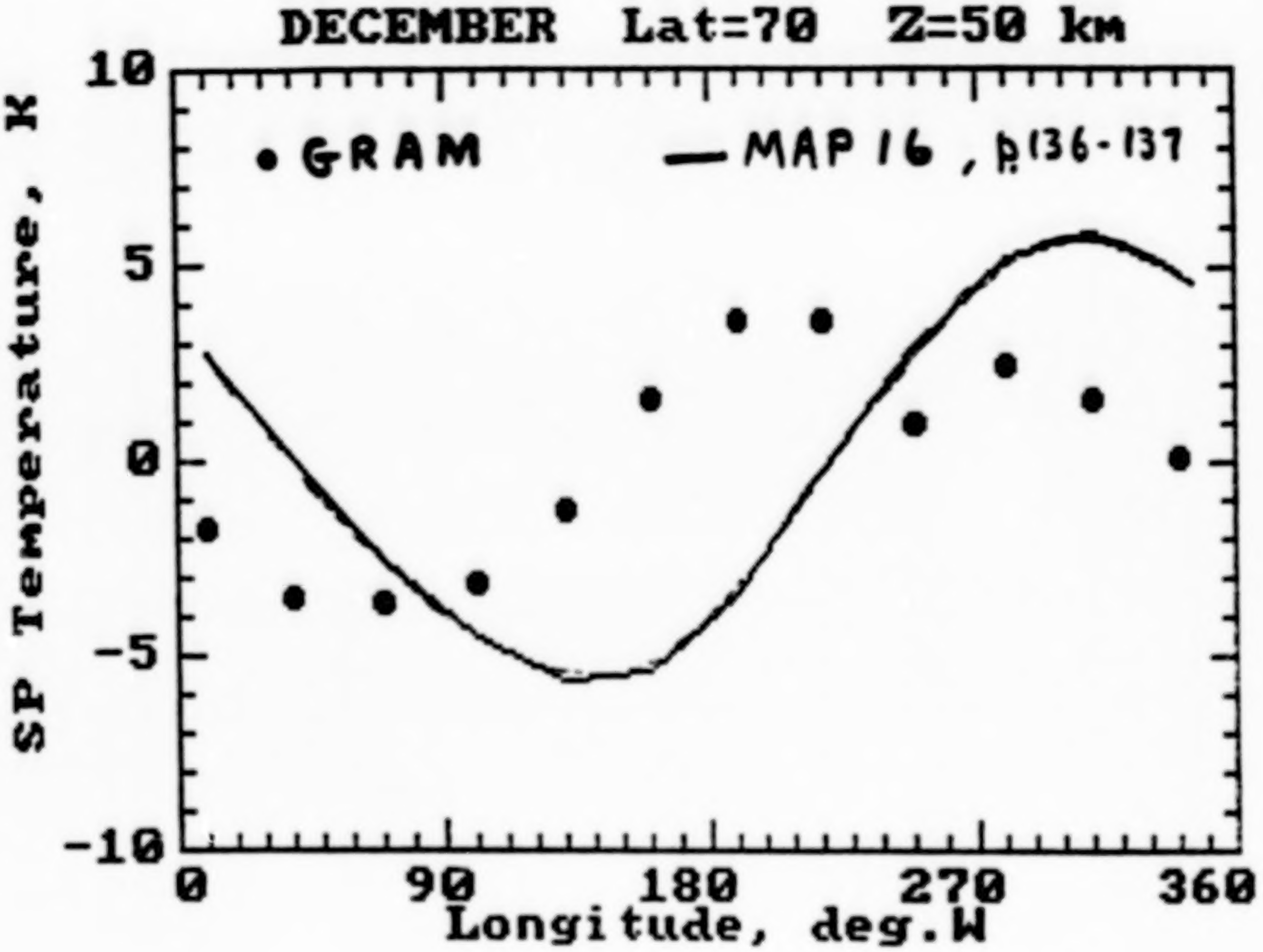
COMPARISONS BETWEEN SHUTTLE DERIVED AND ALTERNATE SOURCES

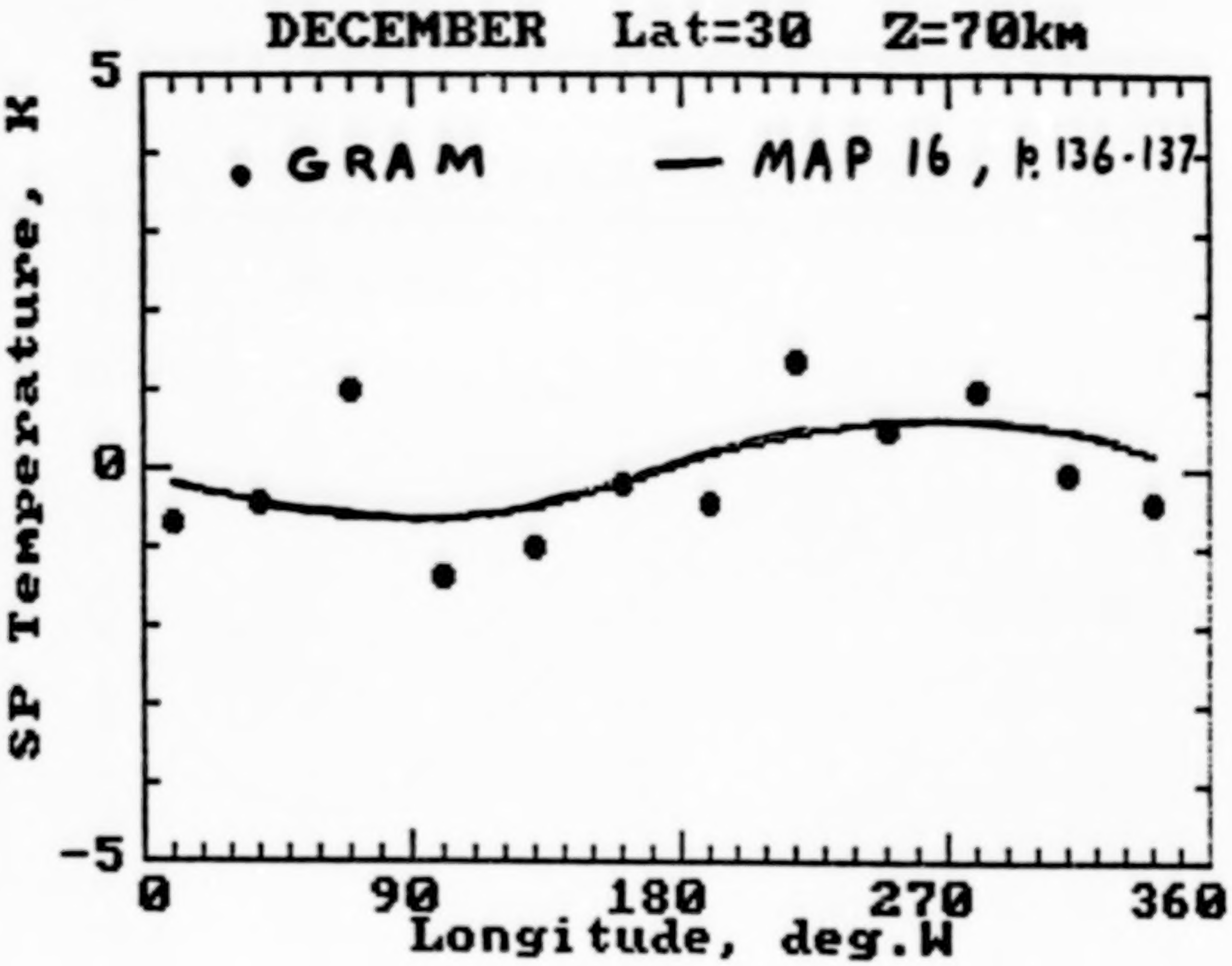

EIELSON AFB JANUARY
90
85
80
75
70
65
60
55
HEIGHT, KM
-10
.0
10
20
30
40
50
60
DENSITY PERTURBATION, %
CIRCLE - 1 KM SPACING
SQUARE - 0.25 KM SPACING


70km Lat=70 x=old __=new
Sigma Density, %
0
5
10
15
20
25
Month
0
3
6
9
12


GRAM
70km Lat=45 x=old •=new
20
15
10
5
0
Sigma Temp., K
0
3
6
9
12
Month
LIDAR, MAP 16, p.312


DECEMBER Lat=70 Z=70 km
● GRAM
— MAP 16, p136-137
SP Temperature, K
10
5
0
-5
-10
0
90
180
270
360
Longitude, deg.W


DECEMBER Lat=70 Z=50 km
• GRAM
— MAP 16, p136-137
SP Temperature, K
10
5
0
-5
-10
0
90
180
270
360
Longitude, deg.W


DECEMBER Lat=30 Z=70km
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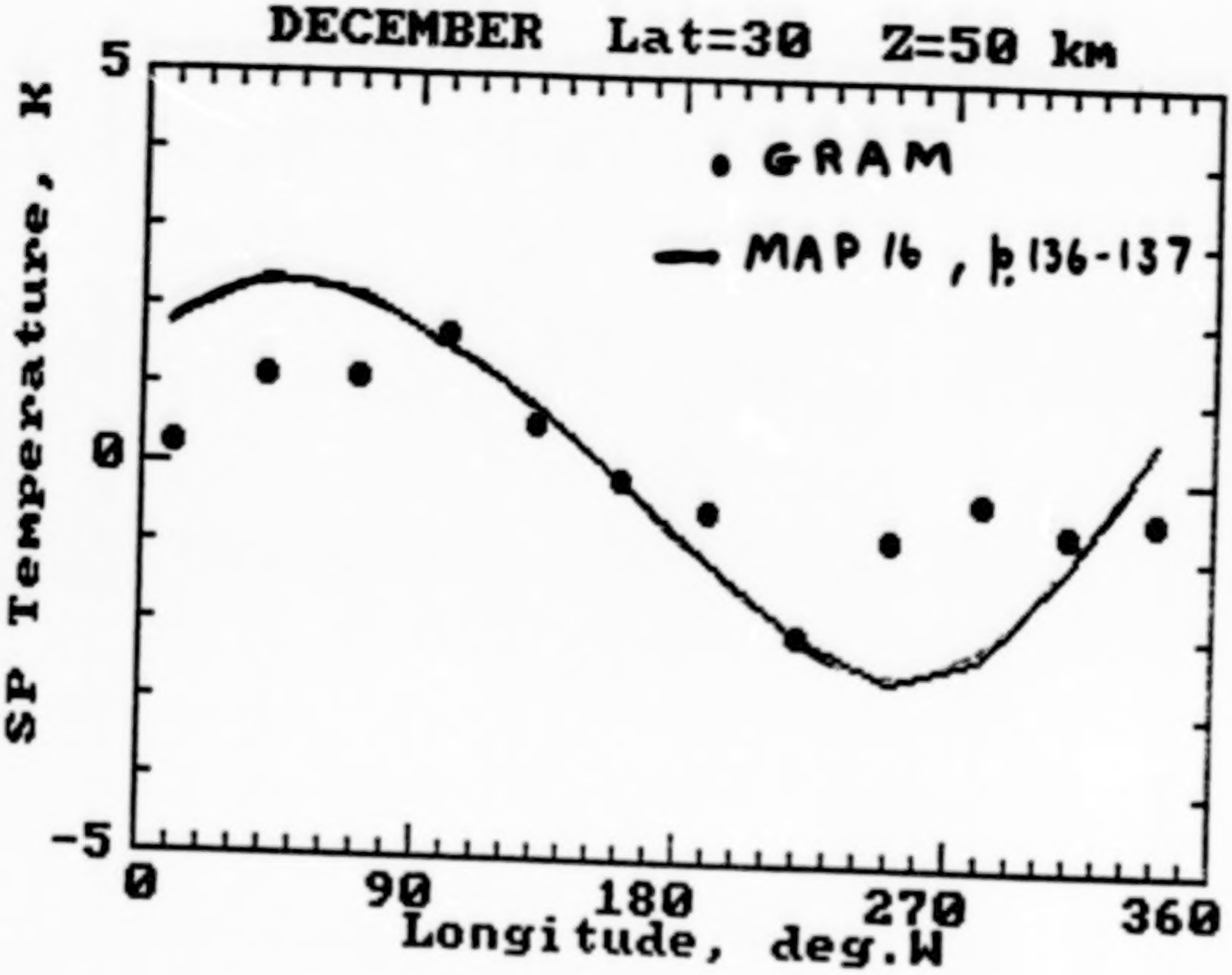
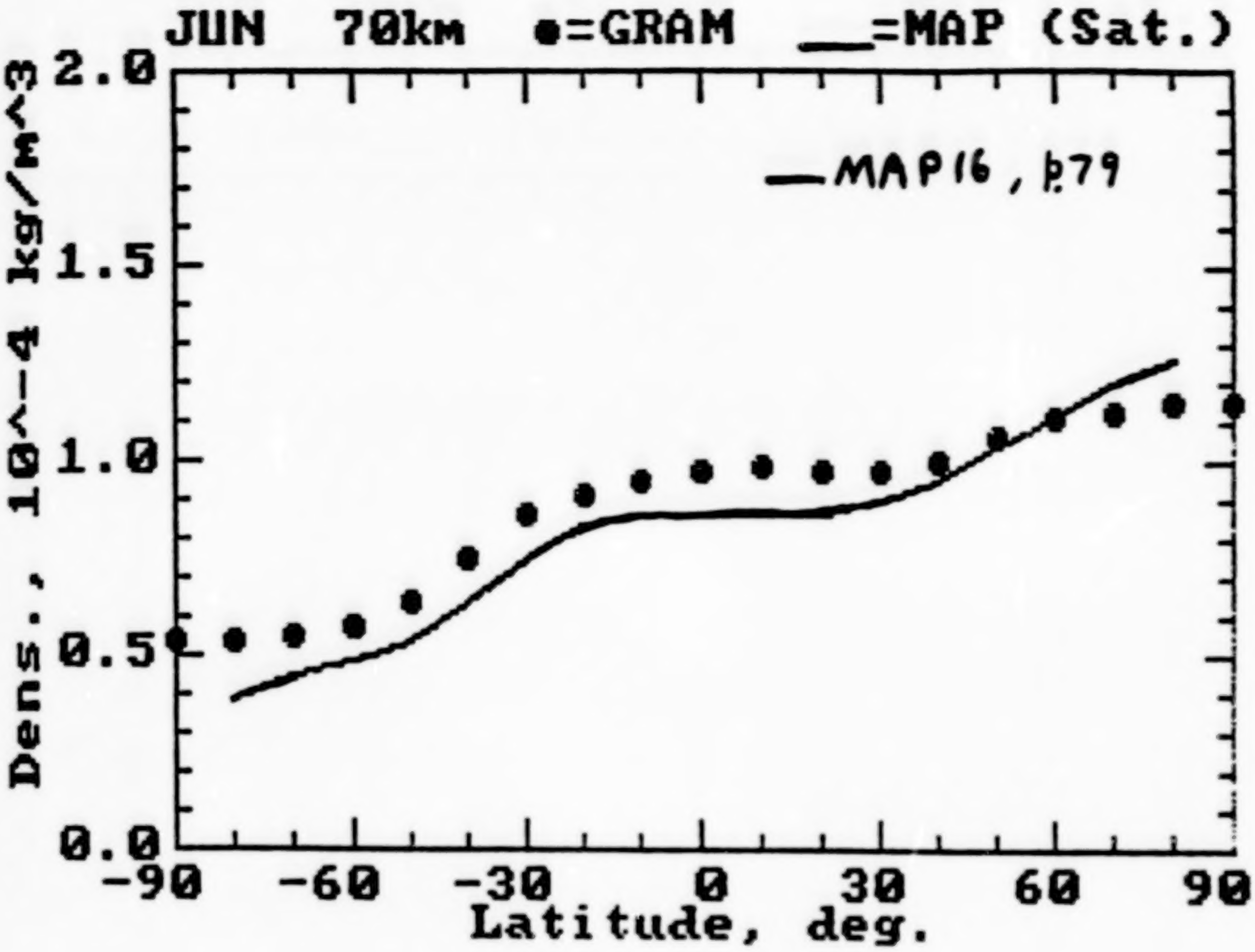
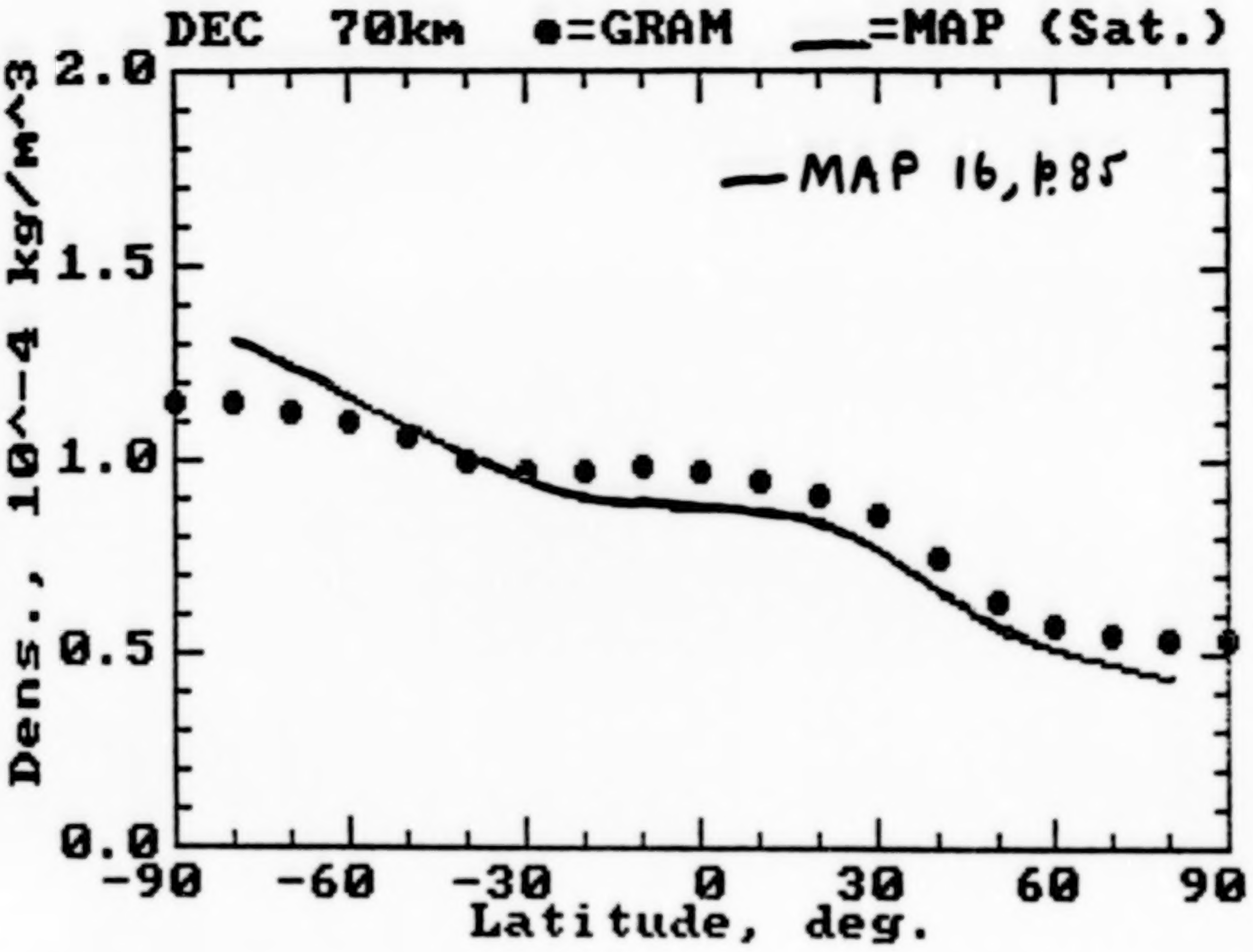
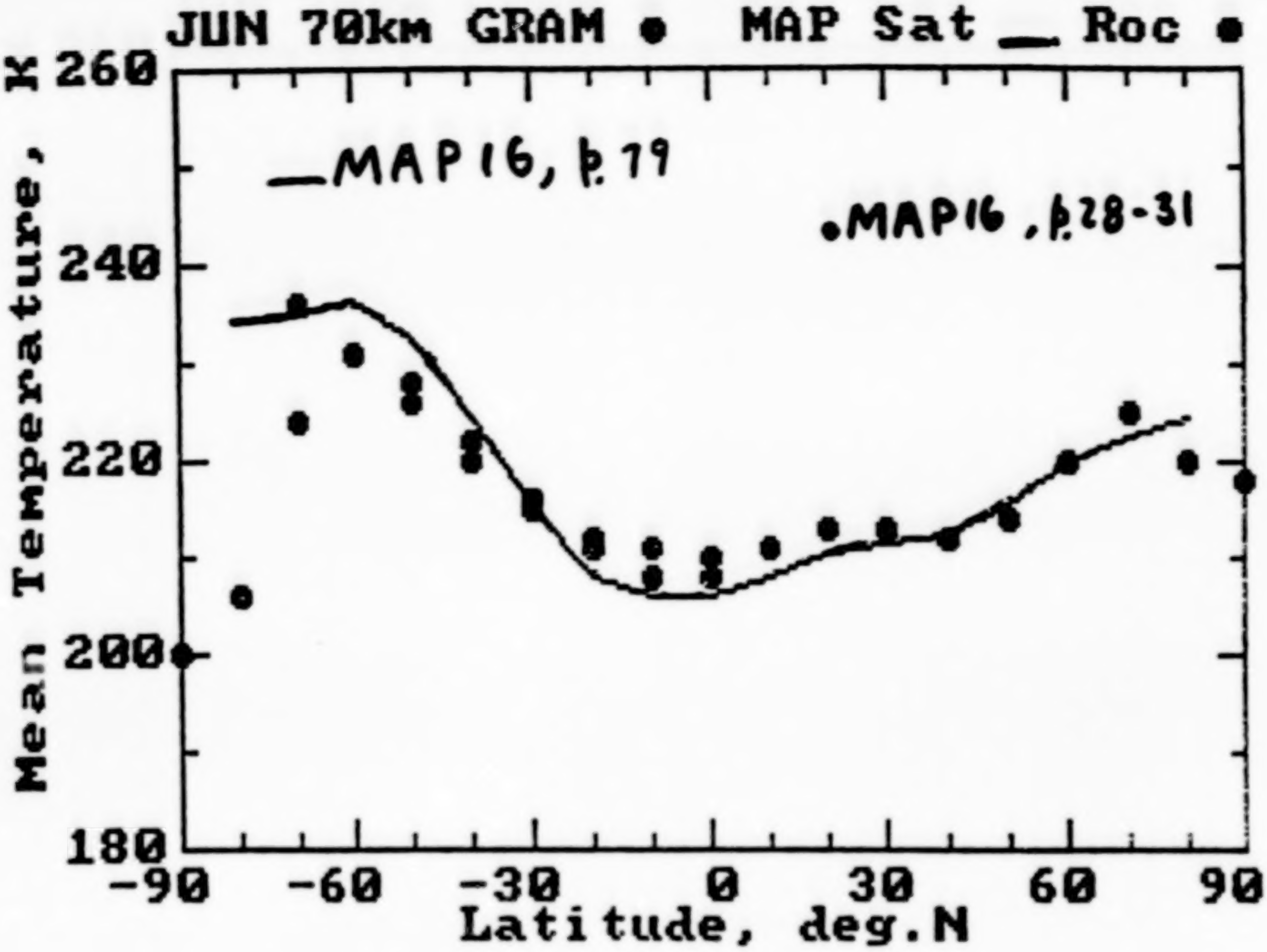
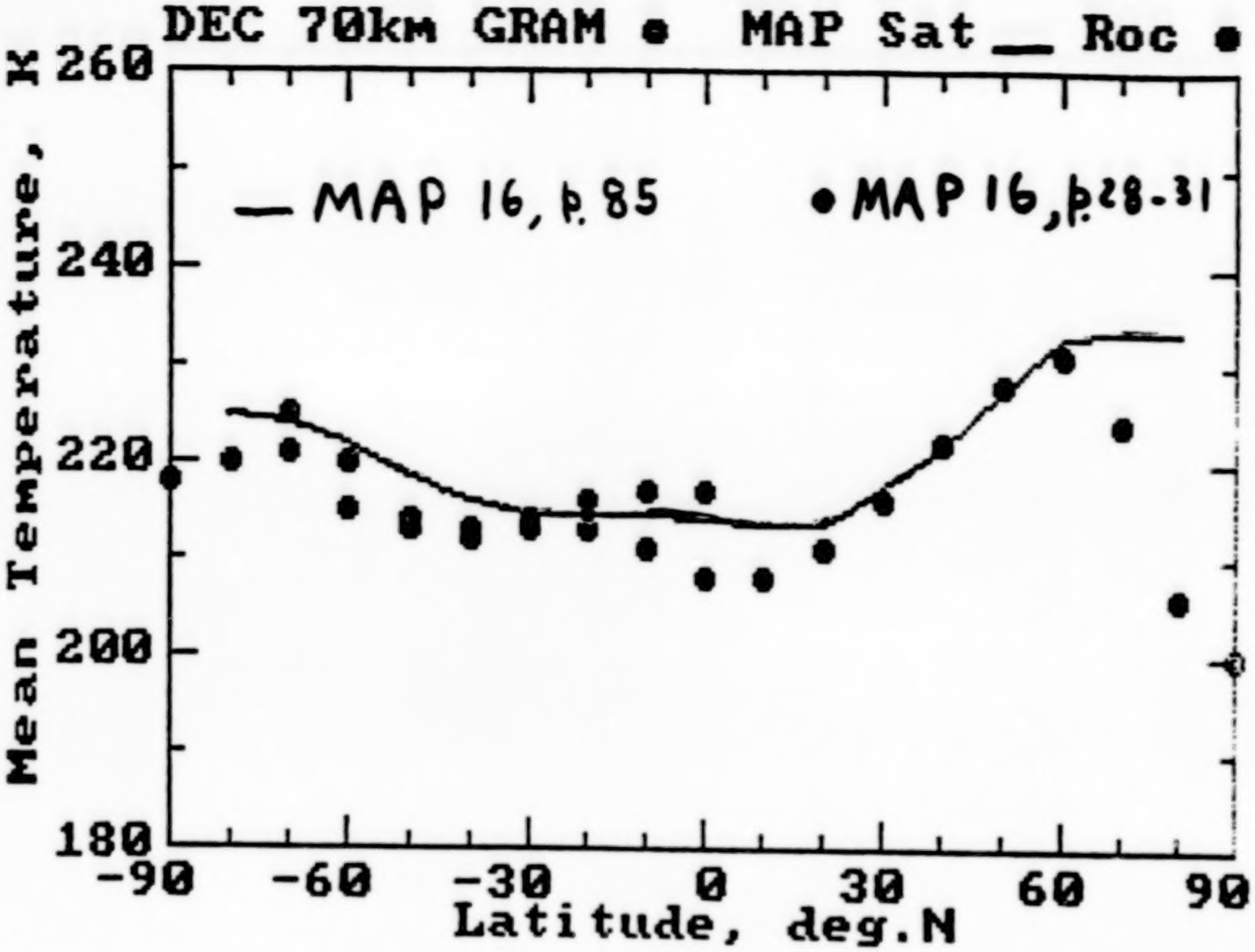
— MAP 16, p. 136-137
SP Temperature, K
5
0
-5
0
90
180
270
360
Longitude, deg.W


DECEMBER Lat=30 Z=50 km
SP Temperature, K
Longitude, deg.W
5
0
-5
0
90
180
270
360
GRAM
MAP 16, p.136-137


JUN 70km ●=GRAM ___=MAP (Sat.)
Dens., 10^-4 kg/m^3
2.0
1.5
1.0
0.5
0.0
—MAP16, p.79
-90
-60
-30
0
30
60
90
Latitude, deg.


DEC 70km ●=GRAM ___=MAP (Sat.)
—MAP 16, p.85
Dens., 10^-4 kg/m^3
2.0
1.5
1.0
0.5
0.0
-90
-60
-30
0
30
60
90
Latitude, deg.


JUN 70km GRAM ● MAP Sat — Roc ●
—MAP16, p.79
•MAP16, p.28-31
Mean Temperature, K
260
240
220
200
180
-90
-60
-30
0
30
60
90
Latitude, deg.N


DEC 70km GRAM ● MAP Sat __ Roc ●
Mean Temperature, K
260
240
220
200
180
— MAP 16, p. 85
● MAP 16, p. 28-31
-90
-60
-30
0
30
60
90
Latitude, deg.N

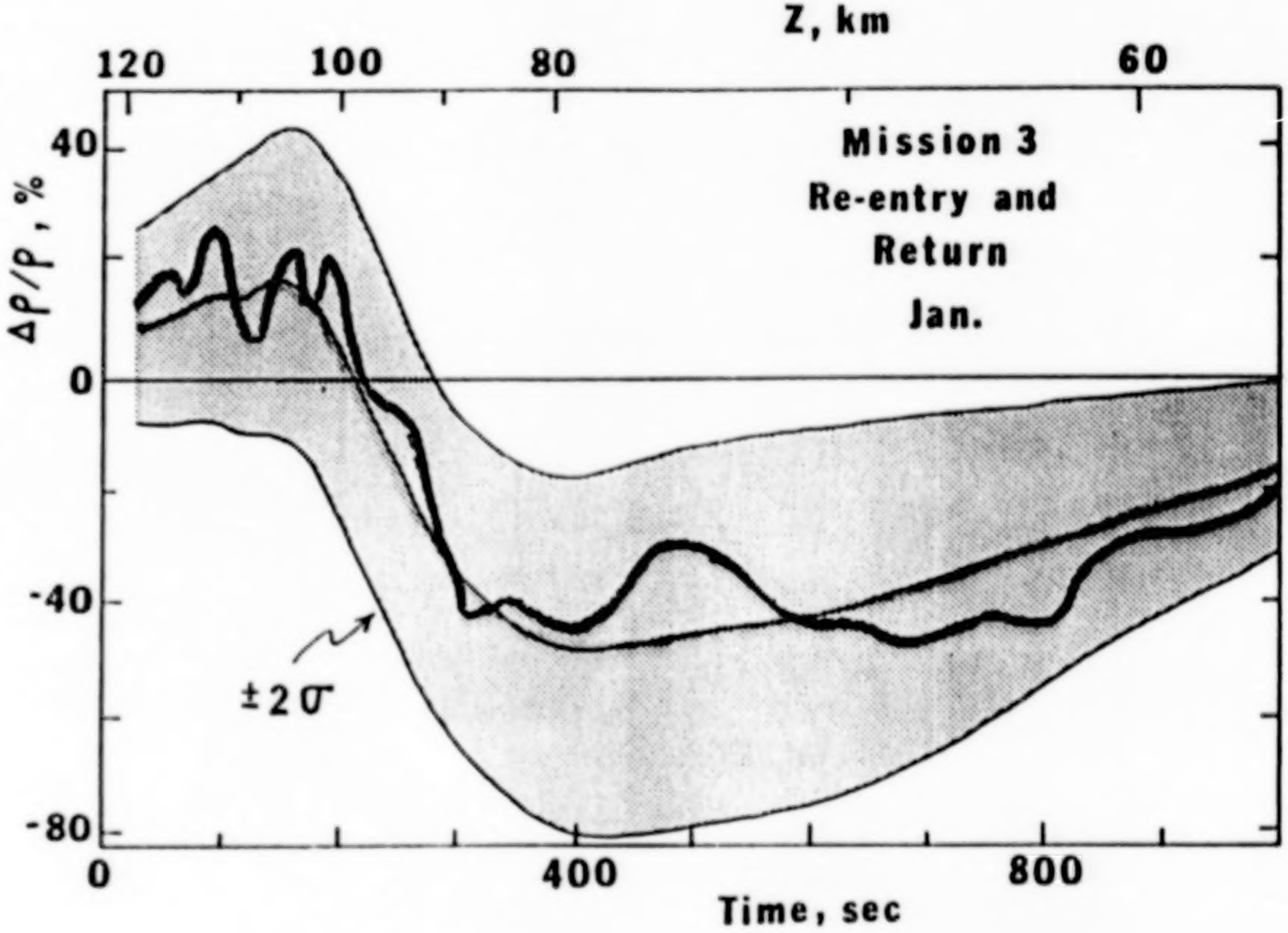


Figure 10.6 Density along a January mission 3 (Vandenburg polar orbit) re-entry and return trajectory. Density deviations are with respect to the 1962 U.S. Standared Atmosphere Graph symbolism as in Figure 10.2.

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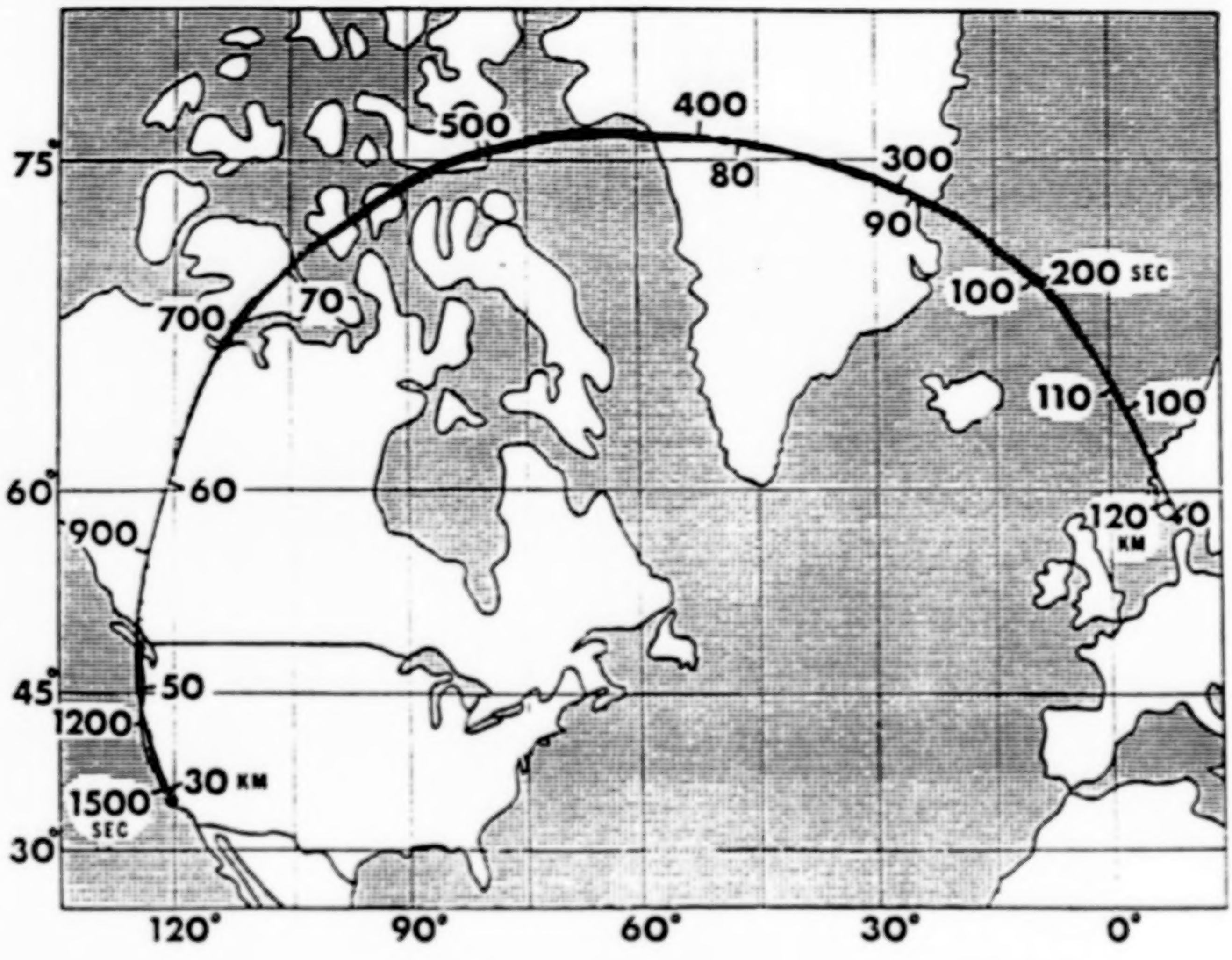
500
400
300
80
90
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200 SEC
110
100
120 KM
0
70
700
60
900
50
1200
30 KM
1500 SEC
75°
60°
45°
30°
120°
90°
60°
30°
0°

Figure 10.5 Ground plot of the re-entry and return trajectory for mission 3, a 104° inclination polar orbit launched from and returning to Vandenburg AFB. The altitude in km is plotted on the inner side of the orbital plot and the time in seconds is plotted on the outer side.

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MIDDLE ATMOSPHERE DENSITY AND MODELS

K. Champion, Air Force Geophysics Laboratory

The 80 to 130 km altitude region is our old "ignorosphere" - the region of the atmosphere that no one seems to be interested in, and yet the critical region for shuttle entry and atmospheric braking. Comparison between the Air Force reference atmosphere and Shuttle IMU data shows large fluctuations at high latitudes. New data sources are available now, such as the Arecibo and Millstone Hill ionospheric scatter radars.

Conclusions:

In the 20-80 km altitude range there is a reasonable quantity of data on the mean atmosphere; however, information on diurnal variability is needed.

In the 80-120 km altitude range data is needed to identify systematic variations and models for the region are preliminary. Unpredictable variations are observed: turbulence, storm effects, gravity waves.

MIDDLE ATMOSPHERE DENSITY AND MODELS

K.S.W. CHAMPION
ATMOSPHERIC SCIENCES DIVISION
AIR FORCE GEOPHYSICS LABORATORY

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SHUTTLE REENTRY DENSITY DATA

AF REFERENCE ATMOSPHERES 1978

DRAFT NEW REFERENCE MIDDLE ATMOSPHERE

A GLOBAL REFERENCE ATMOSPHERE FROM 18 TO 80KM

TIDAL EFFECTS

NEW MODELS FOR 80 TO 120KM

CONCLUSIONS

SHUTTLE LAUNCH AND LANDING DATES AND TIMES

FLIGHT	LAUNCH	LANDING
STS-1	APRIL 12, 1981 0700 EST	APRIL 14, 1981 1021 PST
STS-2	NOVEMBER 12, 1981 1010 EST	NOVEMBER 14, 1981 1323 PST
STS-4	JUNE 27, 1982 1000 EST	JULY 4, 1982 0809 PST
STS-5	NOVEMBER 11, 1982 0719 EST	NOVEMBER 16, 1982 0633 PST

A GLOBAL REFERENCE ATMOSPHERE FROM 18 TO 80KM

BASED ON NORTHERN AND SOUTHERN HEMISPHERE ROCKET DATA AND GLOBAL SATELLITE REMOTE SOUNDING DATA

CONTAINS DISTINCT NORTHERN AND SOUTHERN HEMISPHERE MODELS

ZONAL MEAN MODELS

- TEMPERATURE
- PRESSURE
- DENSITY
- NUMBER DENSITY
- PRESSURE SCALE HEIGHT
- GEOSTROPHIC (W-E) WIND

LONGITUDINAL MODELS

- TEMPERATURE
- PRESSURE
- DENSITY

NEW MODELS FOR 80 TO 120 KM ALTITUDES

BASED ON NORTHERN AND SOUTHERN HEMISPHERE ROCKET DATA AND ARECIBO AND MILLSTONE HILL INCOHERENT SCATTER TEMPERATURES

SINGLE HEMISPHERE MODELS
ZONAL MEAN MODELS

ANALYTIC TEMPERATURE FITS WITH LATITUDE AND ALTITUDE BUT NOT WITH TIME OF YEAR

TEMPERATURES AND PRESSURES FITTED AF REFERENCE ATMOSPHERES AT 68KM

CONCLUSIONS

SHUTTLE REENTRY DATA DEMONSTRATE PROBLEMS

CLIMATOLOGY OR PREDICTABLE VARIATIONS

20-80KM REASONABLE QUANTITY OF DATA
MODELS REASONABLY GOOD

NEED - DIURNAL VARIATIONS, CORRELATION DISTANCES AND TIMES, VARIABILITY

80-120KM REQUIRE ADEQUATE DATA TO IDENTIFY SYSTEMATIC VARIATIONS
MODELS ARE PRELIMINARY

NEED - MORE THEORETICAL AND EMPIRICAL MODELS
MORE DATA WITH GLOBAL AND TEMPORAL COVERAGE

UNPREDICTABLE VARIATIONS

TURBULENCE
STORM EFFECTS IN REAL TIME
LOCATION, AMPLITUDE, PHASE AND VELOCITY OF GRAVITY WAVES

MEASUREMENT TECHNIQUES

Art Belmont, Control Data Corporation

Essentially everything known about the upper atmosphere is based on rocket data. Now that the rocket network is being closed down, there is a dim future for the interpretation of satellite measurements. Belmont's strong suggestion is to increase the rocket network, especially at high latitudes. There is a need for a database for the atmosphere over one complete solar cycle. The atmospheric community needs to come up with new and improved satellite measurement techniques, such as limb observations, lidar, etc. Analysis of four sets of satellite data which cover the years from 1970 to 1982, although not all of them are global, is underway. There is poor vertical resolution in these data and while theoretically data can be retrieved to altitudes of 100 km, 85 km is the practical upper limit. Three or four independent data sets are required to get higher vertical resolution due to the broad weighting functions in the instrument.

DENSITY MEASUREMENTS: ROCKETS VS SATELLITE

F. Schmidlin, NASA/GSFC/WALLOPS

Various density measurement techniques were discussed: grenades, pitot probes, thermistors, rigid sphere, inflatable sphere.

Available data show large variations in density in very short time periods, on the order of tens of minutes. New techniques have been developed for improving falling sphere derived density data. There is a significant improvement at 55 km for wavelengths of 2 km. A 10-15% change in density was measured at 70 km between night and day; however, whether or not it is a true diurnal effect or a problem with the spheres has not been resolved.

A real problem facing the modelers and the users is the reduction of in situ measurements by the rocket network. The interpretation of satellite measurements will suffer from the lack of ground based measurements.

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CONCLUDING SESSION

Chairperson: R. E. Smith

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DISCUSSION

[JoAnn Joselyn] November 13, 1960 was the worst geomagnetic storm known. But we don't actually know what the worst case is, since records have only been kept for 100 years.

Re: geomagnetic activity. We are now at a rather high level, and it will very likely persist. With regard to future capabilities, information useful for forecasts can be obtained from monitoring the solar wind. Recent research on the sun shows promise that solar mechanisms will be understood fairly soon.

Short-term fluctuations: There is no good model for determining what happens at high Ap and F10.7 in the form of short term fluctuations. Nurre proposed looking at the control data on SKYLAB.

Recent density models: J. Liu remarked that the current models do not seem to improve predictions. Reasons for continuing to use the older models are 1) for consistency with the existing database, 2) they run faster.

[Carignan] Much of the discrepancy between models and the real world is from our inability to model small scale structures. A recommendation is that modelers concentrate on this point. With a spherical harmonic approach, the 9th order is quite feasible and wave number 9 would permit modeling the cusp. Another deficiency of current models is in not including dynamics in a useful way. This workshop should endorse the sort of modeling that Roble and Killeen are doing and attempt to incorporate TGCM concepts into models used.

[Hedin] Although it will become possible to obtain direct solar uv data, that will likely not improve the model performance over using F10.7.

On the one hand there are new data sources evolving rapidly that will provide important inputs to density models. On the other hand, there is a huge database that we must maintain continuity with.

[Joe Gamble] It would be most important to bound density variability due to gravity waves.

[Joosten and McCarty] A reliable global model is required. For launches from Vandenberg there is concern about variability at northern latitudes. Entries will probably have to be restricted to coming in from the southern direction, but this cuts significantly into opportunities and into overall shuttle performance.

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[Gamble] We need to verify the results of the perturbation model, particularly for AOTV studies.

[Fritts] We are beginning to understand the motions in the middle atmosphere - gravity waves, equatorial motions, planetary waves. If NASA wants to understand amplitude fluctuations rather than momentum flux, then support will have to be provided for a gravity wave climatology. There are important influences from lower levels. Most motions are due to propagations upward from below, rather than downward from above.

The Workshop was in agreement that the GRAM model is useful, and that the work of Justus and co-workers at Georgia Tech to maintain and improve it should enjoy continued support.

[Vaughan] In the operational world, design decisions will not be made on the basis of forecasting.

CONTRIBUTED STATEMENT

K. Moe

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SIX REASONS WHY THERMOSPHERIC MEASUREMENTS AND MODELS DISAGREE

Kenneth Moe

Department of Geological Sciences
California State University
Fullerton, CA 92634

1. Introduction

One of the persistent themes at this workshop* has been the differences between thermospheric measurements and models. Sometimes the model is in error and at other times the measurements are; but it also is possible for both to be correct, yet have the comparison result in an apparent disagreement. Several of the reasons for disagreement have been pointed out by speakers at the various sessions. Our purpose here is to collect these reasons for disagreement, and, whenever possible, suggest methods of reducing or eliminating them. We shall not discuss calibration, which was not discussed at this meeting, and is extensively reported in the literature.

The six causes of disagreement which we shall discuss are: Actual errors caused by our limited knowledge of gas-surface interactions and by in-track winds; limitations of the thermospheric general circulation models due to incomplete knowledge of the energy sources and sinks as well as incompleteness of the parameterization which must be employed; and limitations imposed on the empirical models by the conceptual framework and the transient waves.

2. Gas-Surface Interactions

Although gas-surface interactions have been extensively studied in the laboratory since the end of World War II, few of these investigations have been directly applicable to satellite problems until the past several years, either because atomic oxygen was not used, or because the energy range was much different from that in the satellite case. One of the problems is that atomic oxygen absorbs on many materials, drastically changing the surface properties from those of the clean surfaces which scientists prefer to study.[1-3]

In order to overcome these limitations, accommodation and drag coefficients were measured in orbit on three paddlewheel satellites.[4-6] The orbital decay responds to the incident momentum, while the spin decay is caused mostly by the reemitted

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* NASA Workshop on Middle and Upper-Atmospheric Modeling as it Applies to Spacecraft Design and Operations, Huntsville, Alabama, Nov. 19-21, 1985.

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momentum. Nevertheless, there still was a parameter which had to be determined from a model; actually, five different models of the angular distribution of reemitted molecules, motivated by laboratory measurements at lower energies, were employed. These models are shown in Fig. 1. All of the models are three-dimensional: The figure actually illustrates their projection on the plane of incidence. The corresponding accommodation coefficients deduced from Ariel 2 which was in an orbit of moderate eccentricity with perigee at 300 km, and Explorer 6, which was in a highly eccentric orbit with perigee near 260 km, are shown in Fig. 2. Beletsky deduced from Proton 2, which was in an orbit of low eccentricity near 190 km, that the Maxwell reflection coefficient was 0.999. These measurements suggested that in orbits of low and moderate eccentricity near 200 km the reflection of molecules is to a close approximation diffuse and completely accommodated. These are the assumptions which have always been used since Sentman[7] first calculated the drag coefficient of a long, attitude-controlled cylinder. The drag coefficient of such a satellite is shown in Fig. 3, which is from an unpublished calculation by Jerome Kainer of the Aerospace Corporation.

At this workshop Marcos[8] has tabulated the ratios of measured density to that computed from many models for four cylindrical satellites and for three satellites of compact shapes. All four cylindrical satellites have ratios to the models 10 to 15% below those of satellites of compact shapes. It therefore appears that there is incomplete accommodation on the long sides of the cylinders, where air molecules strike the satellite at grazing incidence. (Measurements at grazing incidence could not be made using the paddlewheel satellites). Moe and Tsang[9] have supplied equations for applying Schamberg's formalism to data such as those obtained by Marcos. Marcos' result could significantly impact the design of large spacecraft, such as the Space Station. A recalculation of the drag coefficients would also bring the measurements and models closer together.

Another way of learning something about gas-surface interactions in orbit is to compare measurements made by different sensors as the altitude changes.[10] Such a comparison is shown in Table 1. There appear to be systematic variations with altitude. This is an area for future research.

Another kind of comparison[11] which may help us to understand the interaction of helium with surfaces is illustrated in Table 2. It should be obvious that helium will not interact with surfaces in the same way as atomic oxygen does. The analysis of these kinds of satellite data should result in better agreement between measurements and models in the future.

Swenson reported at this workshop that spacecraft glow involves gas-surface interactions. This is an area of research which will affect optical sensors. Plastics seem to glow less, but it is possible that atomic oxygen penetrates the plastic lattice and decomposes it.

3. Errors caused by In-Track Winds

It is well known that the satellite acceleration, a, is

$$a = \frac{1}{2}\frac{\rho V^2 C_d A_N}{M_s}$$

where ρ is the ambient air density, V the velocity of the satellite relative to the air, C_d is the drag coefficient, A_N is the projected area of the satellite normal to the airstream, and M_s is the mass of the satellite.

At low latitudes, and at geomagnetically quiet times, the wind-induced errors in measurements by accelerometers, pressure gauges, and mass spectrometers only amount to 2 or 3%, so they are comparable with some other errors. But at high latitudes during geomagnetic storms, winds of 1 km/s often are measured. The satellite cannot distinguish the effect of its own orbital motion from that of in-track winds when molecules strike it. Because the accelerometer senses momentum transfer, the fractional error in density $\Delta\rho/\rho$ caused by an in-track wind, W, is

$$\frac{\Delta\rho}{\rho} = \left(\frac{V_0 \pm W}{V_0}\right)^2 - 1 = \frac{V_0^2 \pm 2V_0W + W^2}{V_0^2} - 1$$

$$= \pm\frac{2W}{V_0} + \frac{W^2}{V_0^2}$$

If W = 1 km/sec, and V_o = 8 km/sec then

$$\frac{\Delta\rho}{\rho} = \frac{1}{64} \pm \frac{1}{4}$$

This is a 23% or 27% error, depending on whether the wind is blowing in the same direction as the satellite orbital velocity V_o, or in the opposite direction.

In cases in which adsorption can be neglected,[12] the equation for the pressure in a gauge can be written

$$\frac{V_g}{kT}\frac{dp}{dt} = \frac{A_0 n_0 C_{00}}{2\sqrt{\pi}} F(s\cos\psi) - A_0\mu$$

where p is the pressure inside the gauge, V_g is its volume, T its temperature and A_o the area of its orifice; k is Boltzmann's constant, t is the time, n_o is the number density of molecules in the ambient air, C_{oo} the speed of the ambient molecules, and μ

is the number of molecules which strike an area of 1 cm^2 in the gauge from one side in one second. The function $F(s \cos\psi)$ depends on the speed ratio, s, and the angle ψ between the velocity vector and the normal to the orifice.

Because the speed of molecules is so great compared with the dimensions of the gauge, influx and efflux usually reach equilibrium within a hundredth of a second. In equilibrium

$$\mu = n_o C_{oo} \frac{F(s \cos\psi)}{2\sqrt{\pi}}$$

But for $(s \cos\psi) > 3$, which certainly is true if the gauge is pointing into the airstream at 200 km altitude,

$F(s \cos\psi) = 2_s \cos\psi \sqrt{\pi}$, so $\mu_{peak} = n_o C_{oo} s = n_o V$,

where V is the satellite speed relative to the airstream. The ratio of the accelerometer and gauge measurements is then

$$\frac{a}{\mu_{peak}} = \frac{1}{2}\frac{\rho V^2}{n_o V}\frac{C_d A_N}{M_S} = \frac{1}{2}\bar{m}V\left(\frac{C_d A_N}{M_s}\right), \text{ where } V = V_o - W,$$

and $\bar{m}$ is the mean molecular mass. Since a great deal is now known about C_d and $\bar{m}$, and it is easy to measure A_N and M_s, before launch, this method can be used to measure variations of the in-track velocity, V, during geomagnetic storms, and deduce the wind, W. A closed-source mass spectrometer would respond to velocity like a pressure gauge.

At the Meeting, Killeen[13] compared winds deduced from a ground-based Michelson interferometer with those computed by the NCAR Thermospheric General Circulation Model (TGCM). There was gross agreement, but there were large differences locally. The reason is that the TGCM uses a smoothly varying auroral oval, whereas the actual variation of ionospheric conductivity, hence the power input shown in Fig. 4, was complex.[14] It therefore would be helpful to have a method, such as the one just described, for measuring the in-track winds in orbit. Then the air drag could be computed from a model for comparison with that measured, without assuming that that in-track wind was zero.

DIFFICULTIES OF THE TGCM'S
(Sections 4 and 5)

4. Incomplete knowledge of Sources and Sinks

The solar extreme ultraviolet (EUV) radiation, which is an important energy source, is not routinely monitored. Even when it is, the sensors decay rapidly, so it appears that the 10.7 cm solar radio noise $F_{10.7}$ which, like the EUV, originates in the lower chromosphere, will continue to be used as a surrogate (as long as the Canadians continue to monitor it). According to Hinteregger,[15] $F_{10.7}$ sometimes deviates from the EUV by a significant amount for weeks, but Hedin said at the meeting that he has investigated the problem and found $F_{10.7}$ satisfactory for most practical applications.

The large uncertainties in the energy sources are related to the solar wind. Fig. 5 shows Olson's model of the solar wind.[16] The complex interaction of the solar wind with the Earth's magnetic field produces the magnetospheric cavity, which largely shields the thermosphere from direct impingement of the solar wind. However, the solar wind does penetrate through the bow shock into regions of low magnetic field, i.e., the dayside cusps, polar caps, and the tail. Spacecraft measurements show that energy is always being deposited in the thermosphere by particles precipitating through the dayside cusps, although the latitudes at which they precipitate varies with Kp. The resulting heating of the thermosphere was first calculated by Olson.[17]

The energy inputs to the atmosphere through the polar caps and tail are more sporadic, except for the ion drag associated with magnetospheric convection.[18] The magnetic perturbations caused by ionospheric disturbance currents are represented by such indices as Kp, Ap, and AE. There still is controversy about the conditions which permit the entry of solar wind plasma into the magnetosphere and thermosphere, but such parameters as B_y and B_z, which are components of the interplanetary magnetic field, appear to be important. The number density and velocity of the solar wind, which often increase after solar disturbances, are important also.

Kamide and Baumjohann[14] have recently shown that in order to calculate the complicated pattern of Joule heating during a geomagnetic storm, one must first collect the data from 57 magnetometer stations in the Northern Hemisphere and then place these data in Rice University's 3-dimensional ionospheric conductivity model. Only then is one ready to calculate the energy source as a function of space and time. A glance at Fig. 4, which shows the patterns of power production derived by Kamide and Baumjohann at particular times during two substorms, reveals how complicated the patterns are, and how different. (A satellite pass through these changing patterns every 90 minutes could not hope to derive this structure.) The NCAR general circulation model has now been modified so it can accept the total energy derived from this 3-dimensional Joule heating as an input, although the total energy is used simply to expand the auroral oval. The NCAR GCM does have IR cooling by CO_2, but there are several other aspects of the auroral and airglow loss mechanisms which also must be measured, or at least modeled. No doubt these are parameterized in some way in the TGCM. Another important loss mechanism during storms which recently has been discovered is the outflow of 0+ into the geomagnetic tail (the excited polar wind).[19, 20] In addition, the direct energy input from precipitating electrons and protons must also be measured and modeled, if the actual energy inputs are to be used instead of the correlation with Ap, Kp, or AE. This apparently is done in the NCAR calculation.[21]

Actually, only half the Joule heating can be calculated by Kamide and Baumjohann's method, because there are insufficient geomagnetic stations in the Southern Hemisphere to calculate the detailed pattern of ionospheric conductivity there. Since the earth's magnetic field points in opposite directions in the northern and southern hemispheres, and one hemisphere is usually illuminated while the other is dark, the energy input in the two auroral zones could be quite different in magnitude and spatial pattern. Fortunately, there is an approximate alternative method which can be implemented in real time and may be useful for modeling calculations. It was shown 15 years ago that the response of the temperature of a static diffusion model to the net energy inputs from the magnetosphere during storms can be modeled by letting the ionospheric conductivity vary as the 5/4 power of the integrated disturbance currents.[22] This was done as follows: The disturbance currents as a function of latitude and Ap were determined, by using data from 20 magnetic observatories.[23] By integrating the disturbance currents corresponding to various values of Ap, and inserting them in Cole's theory of Joule heating,[24] the temperature increase corresponding with various functional relationships between the ionospheric conductivity and the integrated disturbance current were derived (see Fig. 6). Comparison with the experimental measurements[25] giving the temperature increase in Fig. 7 suggested the relationship

$\sigma \propto J^{5/4}$, where σ is the Cowling conductivity.

Other important processes include the ring current, gravity waves, convection, and turbulence. The ring current, which is indexed by the quantity D_{ST}, is caused by the drift of electrons and protons in the Van Allen belts. The ring current decays by the precipitation of charged particles from low L-shells into the South Atlantic Anomaly, and the auroral and sub-auroral thermosphere. Evidence of this decay can be seen in SAR arcs[26-28] and in red airglow near the South Atlantic Anomaly, but this airglow which identifies the region of energy input is actually a loss mechanism, because the light is escaping from the thermosphere rather than heating it. D_{ST} is largest during geomagnetic storms. It decays to a low level in a few days.

Gravity waves and tidal waves are carrying energy from the lower and middle atmosphere into the thermosphere at all times. In addition, gravity waves generated in the auroral zone, particularly under disturbed conditions, carry energy to low latitudes.[26] Aurorally generated gravity waves are well modeled by GCM's. Hine's[29] Chapman and Lindzen,[30] and Forbes and Marcos[31] have made important contributions to our understanding of waves which propagate into the thermosphere from below. Some of Forbes and Marcos' theoretical predictions of semidiurnal and diurnal variations in the lower thermosphere have been experimentally verified,[32] so it is important to have these tidal variations in the thermospheric models. The NCAR GCM has now included a wave input from below by "Rippling the Boundary". Hedin, et al.[33] found direct evidence of transport processes in the diurnal tide.

Perhaps the most difficult part of the entire circulation problem is to know how to calculate the atmospheric motions near the mesopause, which involve a superposition of laminar and turbulent flows. General circulation models could add greatly to our understanding of this relatively unexplored region if they would treat this interface more realistically. This need can be illustrated by considering atmospheric effects of the dayside cusp precipitation. Fig. 8 shows the electron density at 600 km measured by Alouette 1 in the polar winter, and the corresponding region of dayside cusp precipitation (shaded area).[34] Because the lifetime of electrons is only a few minutes, and because field lines limit diffusion out of the excited region, the region of enhanced ionization does not spread out. But compare the neutral density bulges beneath the dayside cusps measured by Logacs and Spades in Figs. 9 and 10. The neutral bulges have half widths of about 20° in latitude, which could result from motion out of the heated region in response to the pressure gradient. The time it takes for the heat energy to be carried down into the mesosphere and the ratio of atomic oxygen to the molecular constituents are determined by the molecular and eddy conductivities near the mesosphere-thermosphere boundary.[35-36] Fig. 11 shows how composition depends on eddy diffusion. A better understanding of these processes, including their variation with geomagnetic activity,[37] would be helpful in modeling the ionosphere and airglow as well as the neutral atmosphere.

One other difficulty in using TGCM's should be mentioned: How can they calculate the atmospheric variations which result from an unknown cause; e.g., the semiannual variation? Perhaps the modelers will choose to try the recent theory of Walterscheid.[38] Anyone who attempts to compute a realistic model of the thermosphere using a GCM obviously will have a difficult time, but it is well worth the effort: General circulation models are continually adding to our understanding of the important thermospheric processes, and will provide guidance in refining the empirical models which will continue to be used for practical applications.

5. Limitations imposed by the Parameterizations

The errors in the computed winds caused by simply parameterizing the auroral heat input have already been alluded to. Atomic oxygen must be parameterized in some way because the rigid lower boundary at 97 km prevents O from diffusing down into the mesosphere where it recombines. The thousands of auroral lines must somehow be approximated. In spite of the remarkable results achieved by the NCAR TGCM, we have a long way to go before a thermospheric model can be calculated from first principles.

The process described by Mayr, et al. is continuing[39]: "From the theoretical side, one is faced with the problem of solving a large set on nonlinear, partial differential equations in three dimensions that relate the hydrodynamics and electrodynamic properties of the neutral and ionized components in the atmosphere to the energy, mass, and momentum sources of the magnetosphere-thermosphere-lower atmosphere system. We are far removed from such a comprehensive model. With the help of simplified concepts the analysis is just beginning to explore isolated regions and interaction processes to provide understanding and guidance for the development of more sophisticated models."

DIFFICULTIES OF THE EMPIRICAL MODELS
(Sections 6 and 7)

6. Limitations imposed by the conceptual framework

The theory of static diffusion models was developed in the 1950's by Nicolet and Mange.[40] It has been applied most successfully by Jacchia and Slowey.[41] The fundamental idea is that the air expands in a vertical column in response to UV heating and conductive cooling. The models have been modified by Jacchia and Slowey into quite a flexible instrument for representing the real thermosphere and visualizing its response to various energy sources, although it cannot have the flexibility conferred by dozens of harmonics. Judging from the discussion, it has been difficult to include composition realistically in the Jacchia-Slowey models, but they are ideal for calculating density efficiently. Slowey has now added a response to cusp heating. To reduce the discrepancy when comparing these models with measurements, it would be desirable to add a wind vector to them. The wind vector and its standard deviation could be estimated by comparing TGCM calculated winds with the various kinds of wind measurements.

Another type of empirical model, the MSIS, uses spherical harmonics.[42] It appears more successful at representing the composition. It seems less well suited to represent the cusp heating. This is especially true if an ionospheric model along the same lines is planned. As can be seen from Fig. 8, five or ten times as many harmonics would be needed to represent the effect of the cusp on the ionosphere.

The empirical models only require a few input parameters, including $F_{10.7}$ to approximate the EUV, and Ap, Kp, or AE to approximate the net energy input from the solar wind during geomagnetic storms.

7. Waves, which cannot be included in Empirical Models.

The atmosphere is full of gravity waves, which have many sources, and are continually changing. They cannot be included in the empirical models. Two examples are shown in Fig. 12.[43] Although realistic looking waves are produced by the TGCM's of the University of London[44] and NCAR,[21] the actual waves are likely to differ from those modeled at a particular time because of the auroral source is greatly simplified in these models, and the source in tropospheric weather systems is completely excluded. One of the important processes affecting gravity waves is dissipation. This can be measured by the method recently developed by Tedd, et al.[45]

Waves are of little importance in satellite orbital calculations, because they are nearly averaged out by integration; but waves would be important if one had to know the exact density at a particular place and time. The only way to know that is to measure it.

8. Conclusions

In conclusion, there are at least six causes of disagreement between measurements and models, not all of which are caused by the models. TGCM's have made great progress lately, and they, along with wind measurements, will be helpful in improving the empirical models, which will continue to be used for practical calculations.

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TABLE 1.

Correlative Satellite Measurements of Atmospheric Mass Density by Accelerometers, Mass Spectrometers and Ionization Gauges

F. A. MARCOS[*], C. R. PHILBRICK[*] and C. J. RICE[*]

Ratio of Density Measurements at different Altitudes

Altitude (km)	MS/MESA	Number of points	IG/MESA	Number of points
250(D)	0.86 ± 0.12	17	0.98 ± 0.12	22
220(D)	0.79 ± 0.09	16	0.97 ± 0.13	22
190(D)	0.84 ± 0.07	18	1.04 ± 0.08	22
160	1.00 ± 0.10	31	1.09 ± 0.09	22
190(U)	0.91 ± 0.11	31	1.03 ± 0.11	22
220(U)	0.88 ± 0.08	31	0.95 ± 0.07	22
250(U)	0.84 ± 0.11	30	0.94 ± 0.14	22

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TABLE 2.

Intercomparison of Neutral Composition Measurements From the Satellites Esro 4, Aeros A, Aeros B, and Atmosphere Explorer C

H. Trinks, U. von Zahn, C. A. Reber, A. E. Hedin,
N. W. Spencer, D. Krankowsky, P. Lämmerzahl, D. C. Kayser, and A. O. Nier

Mean Density Ratios Obtained From Comparison of the Data of the Neutral Gas Mass Spectrometers Listed in Table 1 for the Gases N_2, O, Ar, and He

	Esro 4, Aeros A		Esro 4, AE-C		AE-C, Aeros B
	$\frac{\rho_{GA}}{\rho_{NATE}}$	$\frac{\rho_{NIMS}}{\rho_{NATE}}$	$\frac{\rho_{GA}}{\rho_{OSS}}$	$\frac{\rho_{NACE}}{\rho_{OSS}}$	$\frac{\rho_{NIMS}}{\rho_{OSS}}$
N_2	0,89	0,65	1,08	1,04	0.79
O	0,77	0,91	1,01	1,07	1.13
Ar	0,62			0.97	
He	0.25		0.48	1.10	0 63

Mean Density Ratios Representing a Comparison of the Measured Densities of Each Experiment With the Mean Density Obtained From All Experiments

	Esro 4 GA	Aeros A Nate	Aeros A Nims	AE-C OSS	AE-C Nace	Aeros b Nims
N_2	1,11	1.24	0,81	1,03	1,07	0,81
O	0,91	1,18	1.07	0,90	0.96	1.02
He	0.53	2.10		1.09	1.20	0.69

The ratios were generated by first calculating the ratio of each spectrometer to Esro 4 GA and then renormalizing by the average.

FIG. 1. FIVE MODELS OF ANGULAR DISTRIBUTION

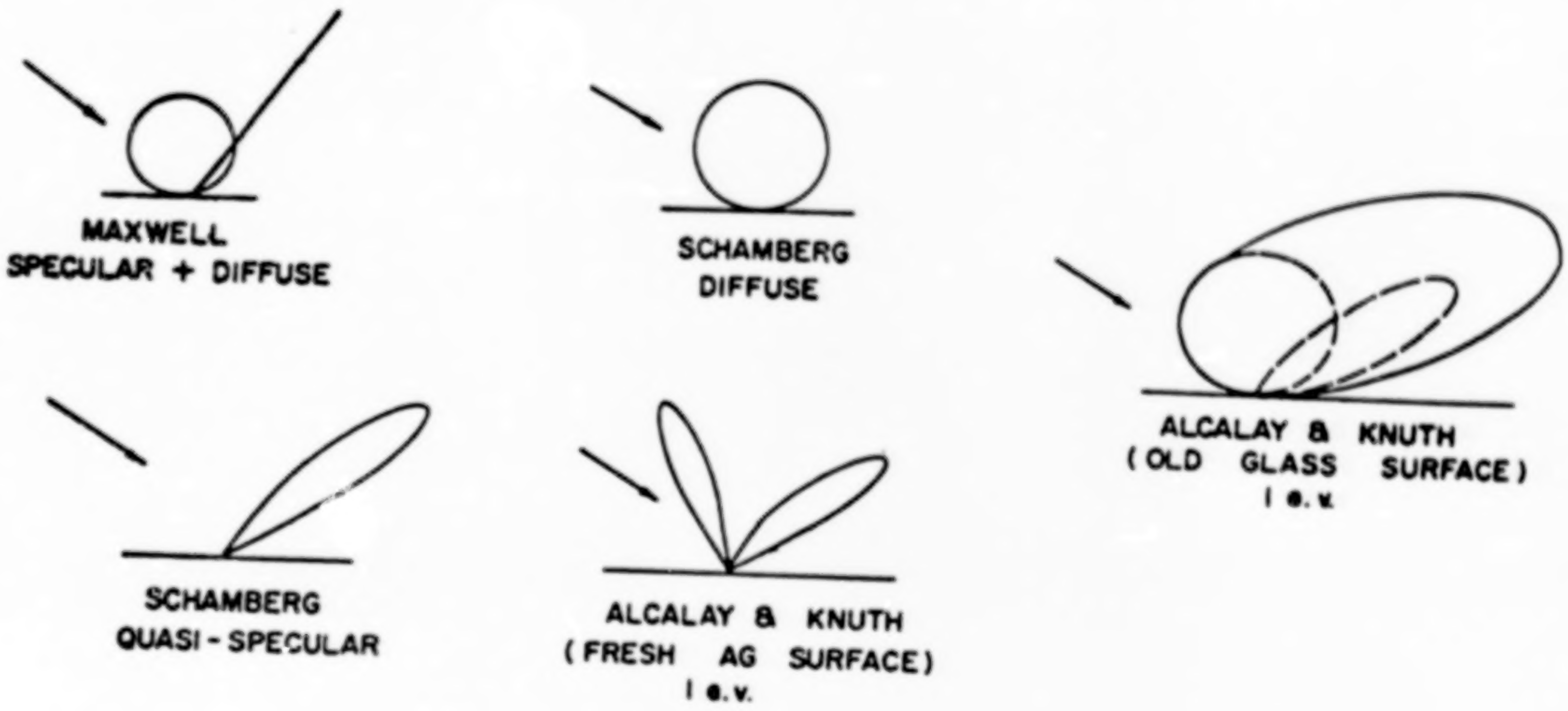
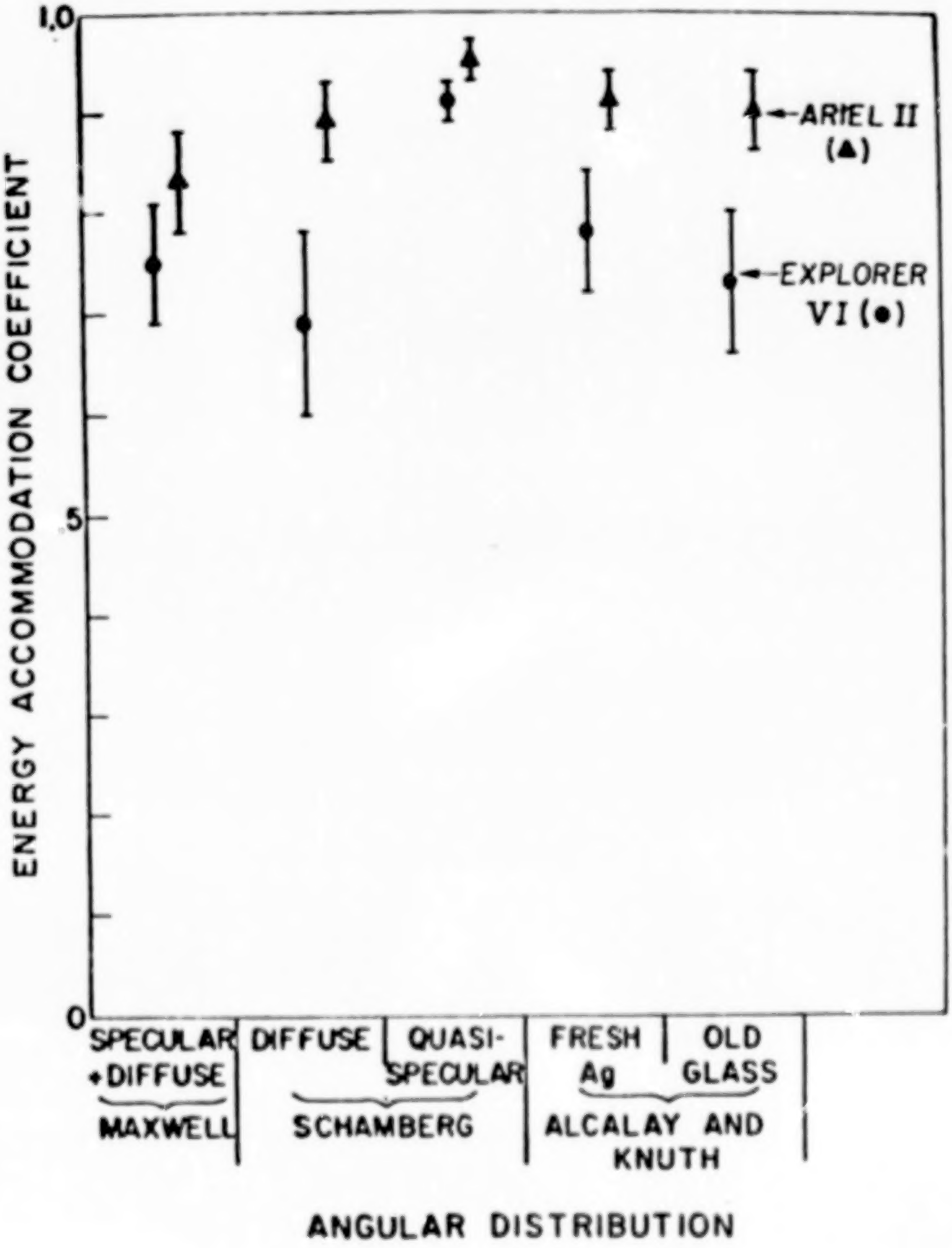

MAXWELL
SPECULAR + DIFFUSE
SCHAMBERG
DIFFUSE
ALCALAY & KNUTH
(OLD GLASS SURFACE)
1 e.v.
SCHAMBERG
QUASI - SPECULAR
ALCALAY & KNUTH
(FRESH AG SURFACE)
1 e.v.

FIG. 2. ACCOMMODATION COEFFICIENTS AS A FUNCTION OF THE ASSUMED ANGULAR DISTRIBUTION



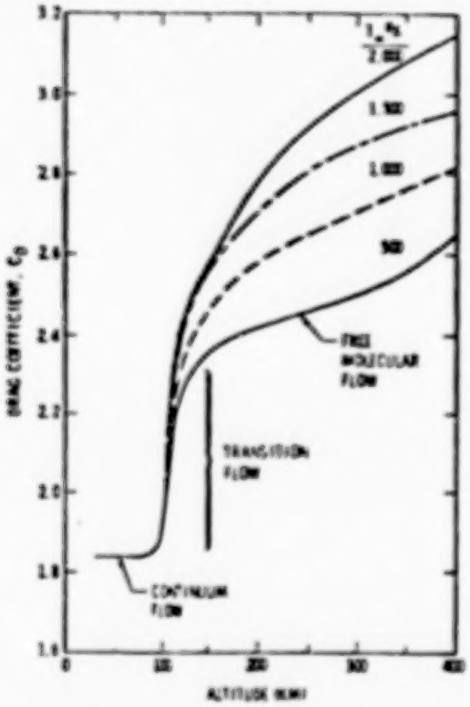
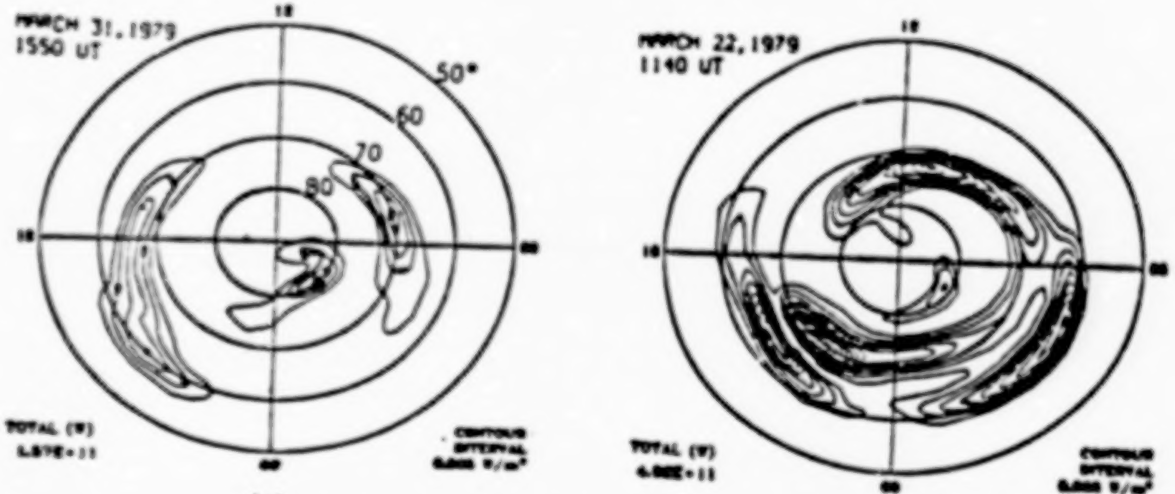


Figure 3. Drag Coefficient of a Cylinder vs Altitude for Various Exospheric Temperatures (L/D = 3)
(AFTER KAINER)

Fig.4.



(a) (b)

Joule heat production rate (contour interval: 0.005 and 0.006 W/m^2 for March 31 and March 22, respectively) for two epochs. The total Joule heating in units of watts is shown on the left-hand bottom corner.

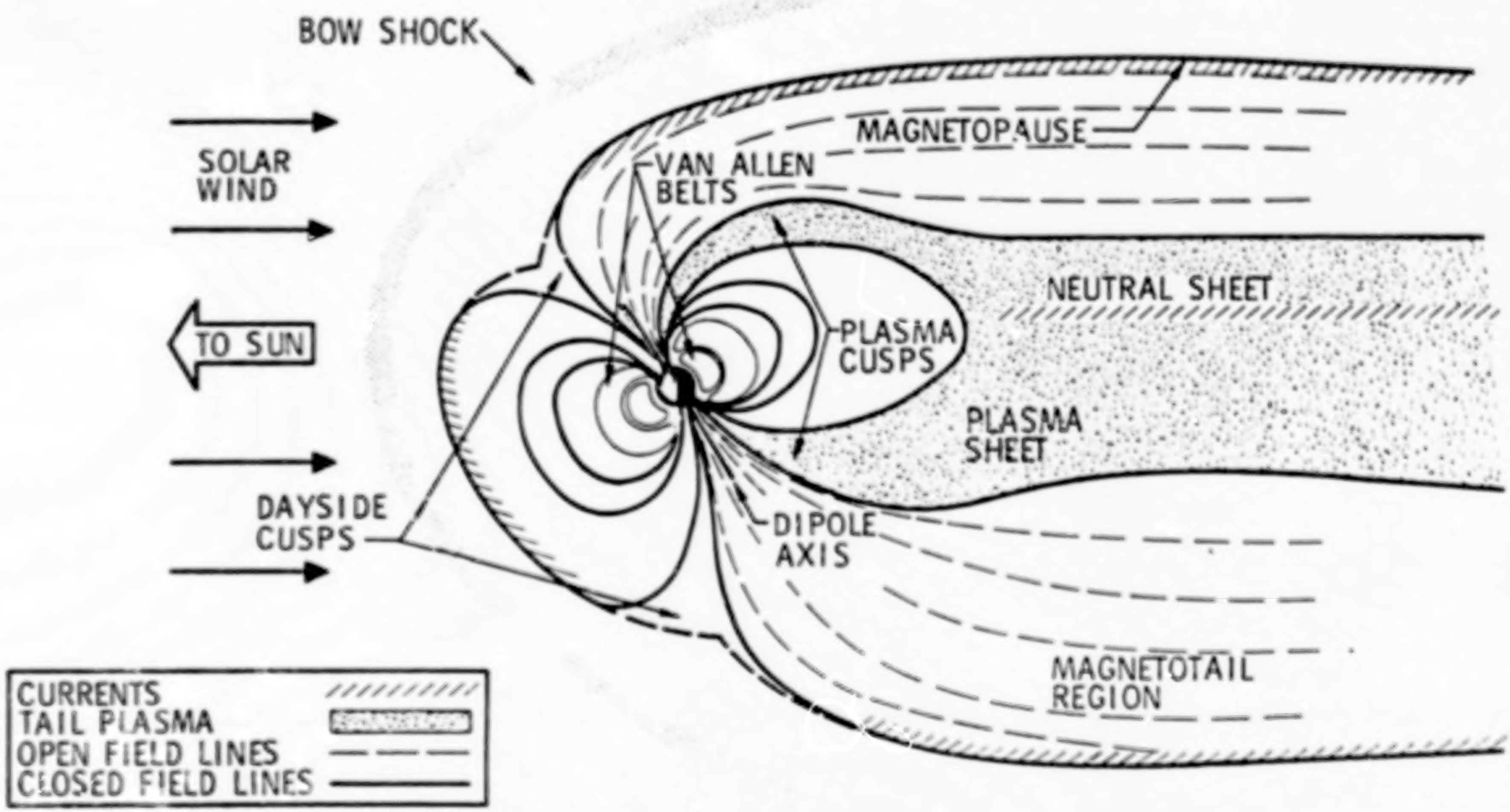

BOW SHOCK
SOLAR WIND
TO SUN
DAYSIDE CUSPS
VAN ALLEN BELTS
MAGNETOPAUSE
PLASMA CUSPS
NEUTRAL SHEET
PLASMA SHEET
DIPOLE AXIS
MAGNETOTAIL REGION
CURRENTS
TAIL PLASMA
OPEN FIELD LINES
CLOSED FIELD LINES

Figure 5 A noon-midnight meridian cross section of the magnetosphere. Shocked solar wind plasma flows continuously down the dayside cusps to the auroral atmosphere. Other particles precipitate intermittently to the high latitude from both open and closed field lines in the tail of the magnetosphere.

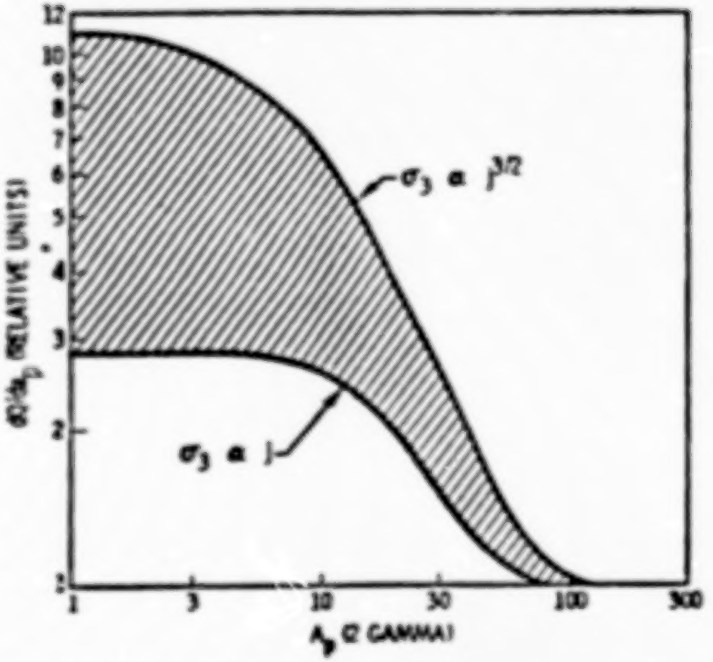


Figure 6. Derivative of Corpuscular Power Input Computed from Measured Storm Ranges at High Latitudes

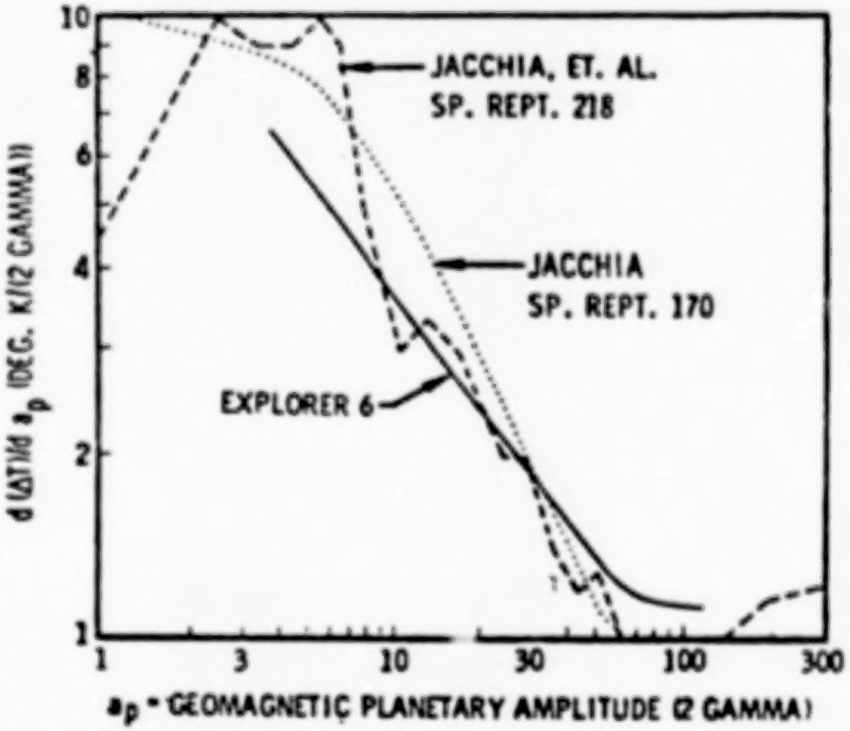


Figure 7. Derivative of Corpuscular Heating Measured by Satellite Drag at Low Latitudes.